Ministry for the Environment
Manatu Mo Te Taiao

Vehicle Emissions and Air Quality

Transport Emissions Study - Modelling and Monitoring

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Air Quality Technical Report No. 6

Executive Summary

This study was commissioned by the Ministry of Transport and the Ministry for the Environment to investigate the nature and impacts on air quality of emissions from motor vehicles in New Zealand to establish:

- what are key factors affecting roadside pollution levels ?
- how can we accurately predict pollutant concentrations near roadways ?

to provide technical input for formulating future policy and management options in the transport sector.

Monitoring and modelling of carbon monoxide was undertaken at three sites, selected as being representative of typical New Zealand roadways. The results show that the model - a modified version of the USEPA approved CAL3QHC - can accurately match observed concentrations for a variety of site and meteorological conditions versus distance. This provides for the first time not only the ability to predict carbon monoxide concentrations at other roadside locations in New Zealand (where monitoring data are not available) but also the capacity to assess typical exposures of the community to these levels.

Field measurements of carbon monoxide (CO) and fine particulates (PM_{10}) took place between 21 January and 14 June 1997 at North Shore in Auckland (a flat motorway), Ngauranga Gorge in Wellington (a hilly motorway), and Riccarton Road in Christchurch (a flat central urban road). Generally, carbon monoxide was found to decrease with distance from the roadway but this occurred in a highly variable but predictable way. The most important factors affecting pollution levels were either source-related (such as vehicle numbers and emission factors) which had a proportional effect or meteorology-related (such as wind speed and atmospheric stability) which exhibited more complex relationships.

All data related to the source characteristics were determined to be consistent with other work being undertaken by the Ministry of Transport as part of the Light Vehicle Fleet Strategy and utilised the same categories of road type, vehicle fleet mix, and traffic flow regimes. The emission factors were developed from vehicle exhaust measurements currently being undertaken using real driving cycles developed specifically for New Zealand conditions as part of a Sustainable Management Fund project sponsored by the Ministry for the Environment.

CAL3QHC was initially applied to the Auckland data for normal to high winds to validate its operation then modified to handle calm conditions which frequently occur in New Zealand and are often associated with high pollution events. The results from the modified model were then compared to observed data. Good agreement was achieved for the trends but the absolute values were under-predicted with observed results being 1.7 times the modelled values.

The most likely explanation for the difference between the modelling and the monitoring results is that the emissions factors used represent average factors developed for specific drive cycles which are composites of many individual events, some of which may have significantly higher emission rates. A future project is planned to establish the typical ranges of emissions versus distance along the roadway. Another factor is the influence of cold-running, which was assumed

to affect only the first three minutes of driving and thereafter was not considered significant. The proportion of vehicles affected was estimated based on the proximity of residential areas to the roadway being studied and it is quite possible that both the effect and proportion of cold-running were higher but further work needs to be done to verify this. As a consequence of these current emission factor assumptions, scaling the results by 1.7 is considered justified and should be utilised for future applications of the model.

For other transport-related pollutants, the results of this and other work has shown that, although fine particulates (PM_{10}) and some hydrocarbons (such as benzene) appear to correlate well with CO, this is not so for nitrogen dioxide (NO_2). More work is needed to refine these relationships, however it is generally accepted that any management strategy developed to reduce emissions of CO to meet air quality guidelines will likely have a similar effect of the emissions of these other pollutants.

In summary, the modelling system is available for wider application throughout NZ, and can be used in many circumstances to make good assessments of effects of emissions from transport provided input data on the meteorology, roadway emissions, site geometry, and existing background concentrations are available.

Meteorology is the most important variable, with the model requiring accurate values of key parameters (e.g. wind speed, atmospheric stability) and estimates of other parameters (e.g. mixing height). For roadway emissions, information is required on traffic volumes, road type (e.g. motorway, central urban), vehicle fleet composition (e.g. light duty petrol, heavy duty diesel), and traffic flow regime (e.g. cold-running, congested, freeflow) to determine the appropriate emissions factors to get the source strength. The site geometry needs to be considered (e.g. number and orientation of roads, the presence of hills, building effects) but many of these are fairly subjective. Some information is needed on the deposition rates (or loss rates) of the contaminant, particularly to the surface, but currently these rates are estimated. Existing background concentrations of the contaminant of interest need to be established, preferably from monitoring information.

The model can be run to produce estimates of effects on either a case-by-case basis, or over longer terms. Although available freely from the USEPA Public Bulletin Board, the model is relatively complex to run so it is highly recommended that this task be performed by someone experienced in dispersion modelling.

After the model is set-up and producing sensible outputs, it can also be used to make an assessment of community or ecosytem exposure to the contaminant of interest by plotting the ground level concentrations and overlaying these with population or ecosystem sensitivity maps.

Finally, the model works well with carbon monoxide and probably will with other simple contaminants which are emitted predominantly from transport (e.g. benzene) but it will not work as well with contaminants which transform in the atmosphere or have wider scale effects (e.g. nitrogen dioxide) unless a much wider network of roads is taken into account.

This study has demonstrated very clearly that the effects of carbon monoxide emissions from transport can be modelled with a high degree of accuracy in many circumstances. It is also

possible to model any given scenario or roadside location if enough information is available. By considering the relevant factors carefully, it is possible to model the effects of other contaminants as well. A future step is to develop and apply models of greater scope, which can cover entire airsheds and be linked to the model used here to give a complete picture of the effects of transport emissions over whole cities.

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1. Introduction

This study was commissioned by the Ministry of Transport and the Ministry for the Environment to investigate the nature and impacts on air quality of emissions from motor vehicles in New Zealand. The results of the work are intended to be used in the future as input into formulating policy and management options in the transport sector.

The principle ***objective*** of this study was to determine the effect of motor vehicle emissions in areas near typical New Zealand roadways. Questions to be addressed included:

- what are key factors affecting roadside pollution levels ?
- how can we accurately predict pollutant concentrations near roadways ?

To achieve this objective the project was separated into several main ***activities***:

- to review work that has been carried out on measuring pollutants such as carbon monoxide, nitrogen dioxide and particulates from 1990 onwards
- to conduct field trials to measure concentration change with distance from the road
- to determine emission source characteristics (e.g. vehicle types, emission factors, traffic behaviour)
- to model vehicle emissions in several different situations and compare the results with the monitoring data to allow more confidence in predicting effects of motor vehicles in New Zealand

This document is the final report for the project and describes all the main activities that have been undertaken in this project with detailed discussion of all of the key findings.

It should be noted that the first activity - review of previous pollution monitoring work in New Zealand - was undertaken by NIWA as part of a Sustainable Management of Air Quality project sponsored by the Ministry for the Environment and has already been reported in the following documents:

1. Nichol S., Petersen J. and Fisher G.,1997: *"Long Term Carbon Monoxide Monitoring in New Zealand: Traffic Impacts Evaluation"*, NIWA Report AK96099 for the Ministry for the Environment, New Zealand
2. Wilkinson M., Petersen J., Fisher G., Chauval R., and Willsman A., 1997: *"Carbon Monoxide Monitoring 1996"*, NIWA Report AK97022 for the Ministry for the Environment, New Zealand
3. Fisher G., 1997: *"Reducing the Air Quality Effects of Vehicle Emissions"*, NIWA Report AK97028 for the Ministry for the Environment, New Zealand

These results will not be discussed in detail in this report.

2. Methodology

2.1 Overview

In general terms, the project comprised three inter-linking parts (see Figure 0.1) covering emission sources, modelling, and monitoring.

For the first part, data on the emissions sources together with information about the local meteorology were gathered and input into the traffic pollution dispersion model (CAL3QHC). This model was then used to predict roadside concentrations of carbon monoxide, which were compared with actual "real-time" measurements collected at the three monitoring sites in Auckland, Wellington and Christchurch.

Determination of the emission sources was considered the least well-defined of the project components (in terms of the certainty of the data). Consequently, feedback from the traffic emissions model and observed monitoring data (including pollutant concentrations and meteorology) were used to refine the assumptions for the emission source data to improve the ability to predict the local effects of vehicle emissions.

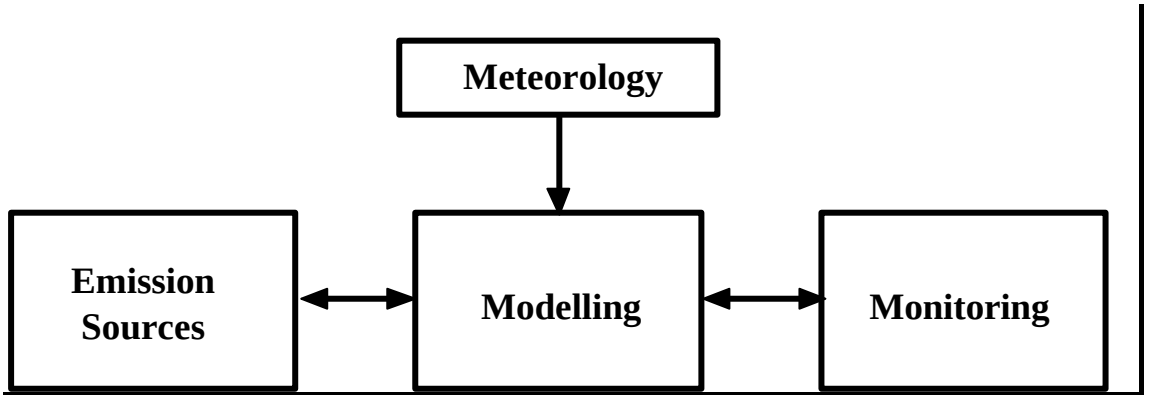

Figure 0.1 Overview of the project

2.2 Emission Source Determination

Source emissions are a function of both the vehicle emissions factors and the vehicle activity (usually measured in vehicle kilometers travelled).

The vehicle emission factors can differ greatly depending on the type of road, vehicle fleet mix, and traffic flow encountered. As a result, emissions factors were determined specifically for each roadside location to ensure that the appropriate input was used for the modelling of subsequent roadway emissions. These site-specific emissions factors were then combined with the vehicle kilometres travelled (VKT) data to give a total emission rate for the road (see Figure 0.2).

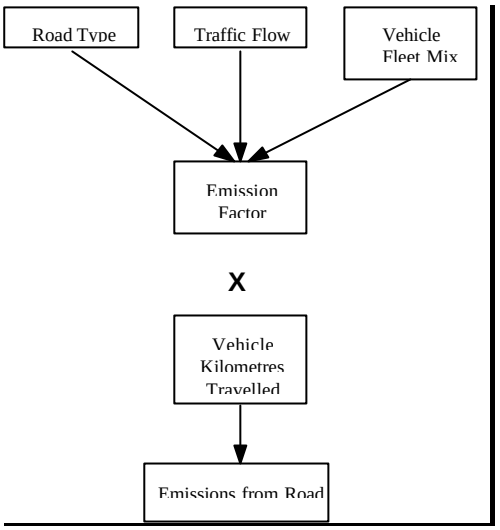

Figure 0.2 Determination of road emissions

The emission factors relevant for each monitoring site were determined considering the following classifications (taken from the emission factor matrices developed by the Fuels & Energy Management Group for the Ministry of Transport as part of the Light Vehicle Fleet Strategy emissions inventory work):

Road Type	Central Urban
	Suburban
	Rural Highway
	Motorway
Vehicle Fleet Mix	Heavy Duty Petrol
	Light Duty Petrol
	Heavy Duty Diesel
	Light Duty Diesel
	Heavy Duty LPG/CNG Vehicles
	Light Duty LPG/CNG Vehicles
	Motorcycles
Traffic Flow	Cold-Running
	Congested
	Interrupted
	Free Flow

Looking at the classifications, each monitoring site covered only one road type (e.g. both Auckland and Wellington sites were designated "motorway" whereas the Christchurch site was designated "central urban"). The vehicle fleet mix was taken from data provided by the Fuels & Energy Management Group, based on the vehicle registration data from 1996 obtained for the Light Vehicle Fleet Strategy work, and was supplemented by field observations. The traffic flow

however varied at each site with time of day or week and required detailed traffic count or speed data for selection of the appropriate regime.

2.3 Monitoring

2.3.1 Site Locations

Monitoring was carried out in Auckland, Wellington and Christchurch as follows:

North Shore, Auckland

The North Shore monitoring site was chosen to represent a busy motorway in a fairly "flat" area. The equipment was located in a sports field of Westlake Girls' High School in Auckland near the Northern motorway.

During "rush-hour", traffic can be very congested on the motorway and nearby Wairau Road (as is the case with many other sections of the Northern motorway) and high levels of emissions can be expected here. The site has relatively few trees and a large area in which to carry out the experiments. In addition, there is an existing air quality monitoring station at the same location which already continuously measures fine particulates (PM_{10}), carbon monoxide and meteorology.

Ngauranga Gorge, Wellington

The Ngauranga Gorge monitoring site was chosen to represent a busy highway located in a canyon. The equipment was located close to the Wellington City Council pumping station adjacent to the motorway on State Highway 1 (SH1) near the junction with State Highway 2 (SH2) north of Wellington.

There are very few roads (aside from the main highway) that are close to the site so any measurements taken are a direct reflection of the emissions resulting from the highway, and are not influenced by other (background) sources.

Riccarton Rd, Christchurch

The Riccarton Road monitoring site was chosen to represent a typical congested central urban road. The equipment was located at the railway crossing at the Hagley Park end of Riccarton Road.

Riccarton Road is one of the busiest roads in Christchurch and has a long history of air quality monitoring.

More detailed information on the sites is provided in *Appendix I.*

2.3.2 Types of Measurement

The principal measurements undertaken at the monitoring sites were as follows:

Carbon Monoxide (CO)

For each monitoring site, carbon monoxide was measured at varying distances from the roadway to determine the concentration profile. The equipment consisted of

electrochemical sensors at up to five locations supplemented with a carbon monoxide analyser at one location. The sensors were mounted on tripods to ensure that they were all at the same height each time monitoring was being carried out.

Carbon monoxide emissions result from incomplete combustion of fossil fuels, with the most significant source being motor transportation. It is readily absorbed from the lungs into the bloodstream where it competes with oxygen for attachment to haemoglobin. Human health effects range from nausea and dizziness in low concentrations up to unconsciousness and death in extreme exposures.

Wind Speed and Wind Direction (WS & WD)

For the Auckland site, wind speed and wind direction data were measured using a meteorological mast at the existing air quality monitoring station located at the same site. For Christchurch and Wellington, temporary mini-meteorological stations were set-up to record hourly wind speed and wind direction. At all locations, site observations were also made of the type of weather conditions that occurred while during the monitoring.

Wind speed and wind direction are critical parameters as they affect the dispersion of carbon monoxide and other pollutants.

Fine Particulates (PM_{10})

For the Auckland site, PM_{10} (fine particulates less than 10 µm) measurements were taken using a TEOM at the existing air quality monitoring station located at the same site. For Christchurch and Wellington, MiniVol samplers were used to measure average PM_{10} concentrations.

Fine particulates are emitted from incomplete combustion of fossil fuels and can result from other pollutants undergoing gas-phase reactions to form fine particles. The principal air quality indicator for adverse health effects from particulates is PM_{10} which represent the portion of the matter that is smaller than 10 µm in diameter and therefore can enter the upper respiratory tract. Exposure to fine particulates can result in symptoms ranging from onset of respiratory symptoms to loss of lung function to lung cancer. These problems occur particularly in the sensitive populations of asthmatics, small children, and the elderly.

Traffic Data

Traffic count data were obtained for all sites from local councils and Transit New Zealand. Site observations were also made of the vehicle mix (e.g. heavy duty versus light duty) and the type of traffic flow (e.g. congested, interrupted, or free flowing).

Traffic count data are needed to determine the strength of the emission source, in this case the roadway.

Table 2.1 that follows summarises the equipment and measurements being taken at each site.

Table 0.1 Monitoring sites for the transport emissions study

Site	Measurement	Method	Location from Roadway
Auckland	CO	CO Sensors	3.2m, 17.2m, 33.2m, 61m (monitoring shed), 73.2m
		CO Analyser	61m (monitoring shed)
	Wind Speed & Direction	Vector wind sensors (on 10m mast)	61m (monitoring shed)
	PM_{10}	TEOM	61m (monitoring shed)
	Traffic	manual counts (supplemented by information from Transit NZ and North Shore City Council)	motorway & Wairau Road
Wellington	CO	CO Sensors	8.6m, 16.6m, 31.7m
		CO Analyser	16.6m (pumping station)
	Wind Speed & Direction	WRE Windlogger (at ~3.4m height)	16.6m (pumping station)
	PM_{10}	MiniVol Sampler	16.6m (pumping station)
	Traffic	manual counts (supplemented by information from Transit NZ)	motorway only
Christchurch	CO	CO Sensors	For first two weeks: 7m, 19m, 30m, 50m, 70m For next two weeks: 7m, 19m, 50m, 120m, plus 45m (other side of road)
		CO Analyser	20m
	Wind Speed & Direction	Unidata wind sensors (at ~1.8m height)	For first two weeks: 30m For next two weeks: 19m
	PM_{10}	MiniVol Sampler	20m (CO analyser site)
	Traffic	information supplied by Christchurch City Council	Riccarton Rd & nearby streets

See *Appendix II* for more detailed information on the equipment being used at each site.

2.4 Modelling

Numerical modelling is used widely in air quality studies both to explain observed concentrations (in terms of geographical and meteorological features, traffic flow patterns, and emission factors) and to make predictions of concentrations (given different scenarios). Modelling formed a significant component of this study but with the aim not to develop a dispersion model for carbon monoxide from motor vehicles from scratch but to apply an existing one, which had already been developed, tested and validated elsewhere, to situations in New Zealand.

The model used in this work was CAL3QHC (*USEPA 1995*), adopted in 1986 by the US EPA as a regulatory model. Recent tests of various models for dispersion from motor vehicles showed that CAL3QHC fared best overall in statistical comparisons between predicted and observed results (*DiCristofaro et al 1994*). Eight models were tested with hourly meteorological, traffic and carbon monoxide data from six different intersections in New York.

CAL3QHC is still in use, despite being 11 years old. The theory of pollution dispersion that it is based on remains valid - the "Gaussian plume" - and, provided its limitations are appreciated, it can be used successfully - and is for many applications. Figure 0.3 below shows the types of input required for the model, with further detail on the exact parameters needed shown in Table 2.2.

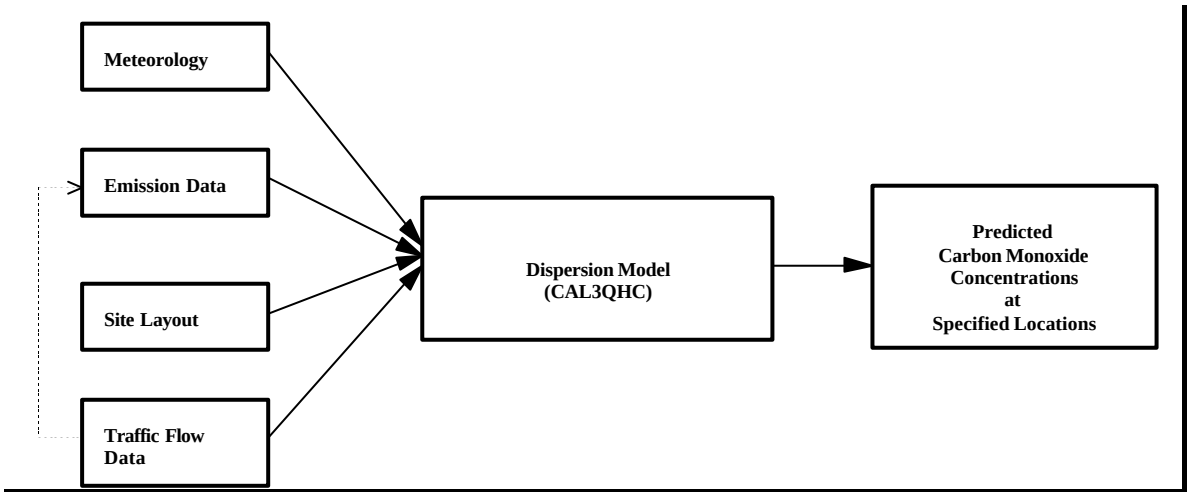

Figure 0.3 Modelling of roadway emissions

A crucial issue when applying the model is the selection of the emissions factors which are key inputs to the model. Methods used to calculate them in the United States are not applicable in New Zealand as they generally utilise output from MOBILE5 (a US model for simulating pollutant emissions) which relies on drive cycle, fleet composition and fuel composition data which differ markedly from New Zealand values. Consequently although CAL3QHC had undergone validation tests abroad, its validity needed to be established for conditions in New Zealand. Therefore, much of the monitoring data collected was used to test the model first before applying it with confidence to situations where there were no observational data.

Table 0.2 Input data required for the CAL3QHC model

Meteorology	Wind Speed Wind Direction Stability/Mixing Height
Emission Data	Depends on location, traffic flows etc. (measured in g/vehicle/km)
Site Layout	Roads and Intersections Locations of interest (for CO predictions)
Traffic Flow Data	Traffic Lights / Phasing Number of Vehicles Queue Lengths

For this study, the overall objectives of the modelling component were:

- to explain observed pollution levels due to motor vehicles and their magnitudes as functions of distance from the roadside
- to provide guidance in the use of the whole modelling system in future applications

3. Results

Carbon monoxide was the primary pollutant of interest in this study, so most of this results section (the first three parts) relate to the emissions monitoring and modelling work undertaken for this contaminant. Other pollutants, fine particulates (PM_{10}) and nitrogen oxides (NOx) are discussed at the end.

3.1 Emission Source Determination

The emission factors relevant for each monitoring site were determined considering the following classifications in discussion with Ian Moncrieff of the Fuels & Energy Management Group. These classifications were consistent with the emission factor matrices developed for the Ministry of Transport as part of the Light Vehicle Fleet Strategy emissions inventory model.

3.1.1 Road Types

The road types selected for the three monitoring locations are shown in Table 3.1 as follows.

Table 3.1 Road type classifications for each monitoring location

Monitoring Location	Road Type
North Shore Auckland	*motorway*
Ngauranga Gorge Wellington	*motorway*
Riccarton Rd Christchurch	*central urban*

Note:

1. Two "motorway" road types were selected to represent different terrain flat (North Shore) and hilly (Ngauranga Gorge)

3.1.2 Vehicle Fleet Mix

The vehicle fleet mix was taken from the vehicle registration data (from 1996) gathered as part of the Light Vehicle Fleet Strategy and provided for the seven vehicle categories by Ian Moncrieff. Figures were supplied for each of the three monitoring locations and also nationally but as the differences between the values were insignificant, a single fleet composition based on the 1996 national figures was chosen to be representative of all sites in New Zealand (see Table 3.2). The percentages shown are based on the % total fleet vehicle kilometers travelled (VKT) and not on vehicle numbers as the activity of each vehicle category is the more important variable. The fleet composition was also confirmed in a survey of traffic composition undertaken in Auckland (*Fisher and Prentice 1996*).

Comparing the 1996 data with earlier results from 1993 (*BCHF 1993*), the biggest change to note in the fleet mix is the increase in activity of light duty diesel vehicles, with their share more than doubling to 9.1% of the total vehicle kilometres travelled. Light duty petrol vehicles continue to dominate the fleet at around 80% and heavy duty diesel vehicles remain a significant contributor at approximately 8%.

Table 3.2 Vehicle fleet mix used for the emissions study compared to previous vehicle fleet mix from 1993

Vehicle Type	1996 Fleet %	1993 Fleet %
Light Duty Petrol	*79.8%*	82.3%
Light Duty Diesel	*9.1%*	4.1%
Light Duty CNG/LPG	*1.9%*	2.7%
Heavy Duty Petrol	*0.7%*	1.6%
Heavy Duty Diesel	*8.1%*	8.4%
Heavy Duty CNG/LPG	*0%*	0.2%
Motorcycles	*0.4%*	0.7%

All figures above are in terms of %VKT.

Note:
1. Light Duty means <3.5 tonnes
2. Heavy Duty means >3.5 tonnes
3. Motorcycles are assumed 60% 2-stroke & 40% 4-stroke engines

3.1.3 Traffic Flow - General Emission Factors

From his related work with the Light Vehicle Fleet Strategy emissions inventory model, Ian Moncrieff produced sets of composite emission factors for the light duty petrol portion of the vehicle fleet for the four different traffic flow regimes of cold running, congested, interrupted, and free flow on the two road types applying to this study - motorway and central urban. These factors were developed specifically for New Zealand driving conditions as part of the Sustainable Management Fund Vehicle Emissions Testing Project being conducted by Auckland UniServices Ltd (*UniServices 1997*) and sponsored by the Ministry forthe Environment. The results showed significantly higher emissions of carbon monoxide arising from the actual New Zealand driving cycles than from overseas test driving cycles (which had been used previously to derive emission factors in transport studies in this country).

For the remainder of the fleet, emission factors were developed from a survey of the literature (*Economopoulos 1993, GANZ 1995, IPCC 1995*) but these were checked against the latest New Zealand emission factors (for light duty petrol vehicles) to ensure that the relativities between vehicle types remained realistic. These factors are contained in *Appendix III*.

In order to apply these factors, the traffic flow regime needed to be established at each monitoring location of interest using traffic count data and average speed data (if available). This process is illustrated in the next section on the specific emission factors used for each monitoring site.

3.1.4 Traffic Flow - Specific Emission Factors

For all monitoring sites, traffic count data and average speed data (where possible) were obtained from either Transit New Zealand or local council records (see *Appendix IV*). These showed that the traffic numbers and traffic flow regimes varied significantly with time of day, requiring different emission factors to be used at different times of day also.

Most sites exhibited periods of congested and interrupted flow indicated by either a drop in average speed or inferred from a significant increase in vehicle numbers. These conditions were assessed separately for both directions of travel on the road as the "rush hour" conditions were not uniform and depended on the destination. In addition some allowance for cold running was also necessary to compensate for vehicles travelling on the monitored road in a cold state, but this was dependent on the proximity of residential housing and other feeder roads.

From a detailed investigation of all traffic patterns relating to the monitoring sites, the worst case traffic flow regimes were assumed from the data to arrive at the specific emission factors summarised for each monitoring site in the following tables.

North Shore - Auckland

The appropriate traffic flow regimes and corresponding emission factors used as modelling input are summarised in Tables 3.3 and 3.4 respectively.

The key assumption to note is that no allowance was made for "cold running" at this site as vehicles were assumed to have taken longer than three minutes to get to the motorway. This was based on the proximity of residential areas, motorway on-ramps, and other feeder roads.

Table 3.3 Traffic flow regimes determined for the North Shore site

Time of Day	Northbound	Southbound
00:00 to 06:00	freeflow	freeflow
06:00 to 10:00	freeflow	***congested***
10:00 to 16:00	freeflow	freeflow
16:00 to 19:00	*interrupted*	freeflow
19:00 to 24:00	freeflow	freeflow

Table 3.4 Corresponding emission factors applicable to the North Shore site

		CO Emissions in g/km driven			
Vehicle Type	**Total Fleet %**	**Cold Running**	**Congested**	**Interrupted**	**Freeflow**
LD Petrol	79.8%	57.70	19.90	13.30	10.00
LD Diesel	9.1%	n/a	0.85	0.85	0.85
LD LPG/CNG	1.9%	n/a	1.42	0.84	0.61
HD Petrol	0.7%	n/a	70.00	55.00	50.00
HD Diesel	8.1%	n/a	7.03	3.36	2.72
HD LPG/CNG	0.0%	n/a	18.86	18.86	18.86
Motorcycles	0.4%	n/a	18.80	18.80	18.80
Fleet Total	**100.0%**	**n/a**	**17.12**	**11.44**	**8.71**

Note:

1. LD = light duty vehicles < 3.5 tonnes
2. HD = heavy duty vehicles > 3.5 tonnes
3. motorcycles are assumed to be 60% 2-stroke: 40% 4-stroke engines
4. n/a = factors not available
5. no "cold running" occurs at North Shore as vehicles take longer than 3 minutes to get to the motorway.

Ngauranga Gorge - Wellington

The appropriate traffic flow regimes and corresponding emission factors used as modelling input are summarised in Tables 3.5 and 3.6 respectively.

The first key assumption to note is that no allowance was made for "cold running" at this site as vehicles were assumed to have taken longer than three minutes to get to the motorway. This was based on the proximity of residential areas, motorway on-ramps, and other feeder roads.

Table 3.5 Traffic flow regimes determined for the Ngauranga Gorge site

Time of Day	**Downhill**	**Uphill**
00:00 to 07:00	freeflow	freeflow
07:00 to 09:00	***congested***	freeflow
09:00 to 12:00	*interrupted*	freeflow
12:00 to 15:00	*interrupted*	*interrupted*
15:00 to 18:00	*interrupted*	***congested***
18:00 to 19:00	freeflow	*interrupted*
19:00 to 24:00	freeflow	freeflow

In addition, the emission factors were modified for the uphill traffic to compensate for the steep incline encountered. In the case of heavy duty vehicles, all factors were set at the worst case for all regimes to approximate the realistic low speed and engine load characteristics. For light duty vehicles, the "interrupted" and "freeflow" factors were averaged across the next flow regimes to adjust for the lower speeds and higher engine loads but not to the same extent as in the heavy duty case. The downhill traffic emission factors remained consistent with normal motorway conditions.

Table 3.6 Corresponding emission factors applicable to the Ngauranga Gorge site

		CO Emissions in g/km driven "downhill"			
Vehicle Type	**Total Fleet %**	**Cold Running**	**Congested**	**Interrupted**	**Freeflow**
LD Petrol	79.8%	57.70	19.90	13.30	10.00
LD Diesel	9.1%	n/a	0.85	0.85	0.85
LD LPG/CNG	1.9%	n/a	1.42	0.84	0.61
HD Petrol	0.7%	n/a	70.00	55.00	50.00
HD Diesel	8.1%	n/a	7.03	3.36	2.72
HD LPG/CNG	0.0%	n/a	18.86	18.86	18.86
Motorcycles	0.4%	n/a	18.80	18.80	18.80
Fleet Total	**100.0%**	**n/a**	**17.12**	**11.44**	**8.71**

		CO Emissions in g/km driven "uphill"			
Vehicle Type	**Total Fleet %**	**Cold Running**	**Congested**	**Interrupted**	**Freeflow**
LD Petrol	79.8%	57.70	19.90	16.60	13.30
LD Diesel	9.1%	n/a	0.85	0.85	0.85
LD LPG/CNG	1.9%	n/a	1.42	1.13	0.84
HD Petrol	0.7%	n/a	70.00	70.00	70.00
HD Diesel	8.1%	n/a	7.03	7.03	7.03
HD LPG/CNG	0.0%	n/a	18.86	18.86	18.86
Motorcycles	0.4%	n/a	18.80	18.80	18.80
Fleet Total	**100.0%**	**n/a**	**17.12**	**14.48**	**11.84**

Note:

1. LD = light duty vehicles < 3.5 tonnes
2. HD = heavy duty vehicles > 3.5 tonnes
3. motorcycles are assumed to be 60% 2-stroke: 40% 4-stroke engines
4. for HD vehicles, emission factors have been set at worst case for all regimes due to the steep incline
5. for LD vehicles, emission factors have been adjusted for "interrupted" & "free" to compensate for the steep incline

6. no “cold running” occurs at Ngauranga Gorge as vehicles take longer than 3 minutes to get to the motorway.

Riccarton Road - Christchurch

The appropriate traffic flow regimes and corresponding emission factors used as modelling input are summarised in Tables 3.7 and 3.8 respectively.

The key assumption to note is that a 20% allowance was made for "cold running" at this site. This was because the site was located in the midst of a residential area and a certain fraction of the vehicles would have started their journey locally.

Table 3.7 Traffic flow regimes determined for the Riccarton Road site

Time of Day	Eastbound	Westbound
00:00 to 07:00	freeflow	freeflow
07:00 to 08:00	*interrupted*	*interrupted*
08:00 to 18:00	***congested***	***congested***
18:00 to 19:00	*interrupted*	***congested***
19:00 to 21:00	*interrupted*	*interrupted*
21:00 to 24:00	freeflow	freeflow

Table 3.8 Corresponding emission factors applicable to the Riccarton Road site

		CO Emissions in g/km driven			
Vehicle Type	**Total Fleet %**	**Cold Running**	**Congested**	**Interrupted**	**Freeflow**
LD Petrol	79.8%	93.40	46.70	33.20	19.90
LD Diesel	9.1%	n/a	0.85	0.85	0.85
LD LPG/CNG	1.9%	n/a	1.42	1.13	0.61
HD Petrol	0.7%	n/a	70.00	62.50	55.00
HD Diesel	8.1%	n/a	7.03	5.20	3.36
HD LPG/CNG	0.0%	n/a	18.86	18.86	18.86
Motorcycles	0.4%	n/a	18.80	18.80	18.80
Fleet Total	**100.0%**	**n/a**	**38.51**	**27.53**	**16.71**

Note:

1. LD = light duty vehicles < 3.5 tonnes
2. HD = heavy duty vehicles > 3.5 tonnes
3. motorcycles are assumed to be 60% 2-stroke: 40% 4-stroke engines
4. 20% "cold running" occurs at Riccarton Road as vehicles are coming from local areas i.e. for a LD petrol vehicle in congested mode, CO
   = 0.2*93.40 + 0.8*46.70 = 56.04 g per km driven

3.2 CO Monitoring

Monitoring of carbon monoxide was undertaken at the three sites between 21 January and 14 June 1997 (see *Appendix V* for all results). The results are discussed in more detail in the following sections relating to each site.

3.2.1 CO Results for North Shore - Auckland

Carbon monoxide was monitored for five periods comprising four "overnight" periods (running from afternoon one day to midday the next) and one "extended" period (running for four weekdays continuously) at the North Shore site between 21 January and 21 March 1997. Monitoring was scheduled for days with predicted westerly conditions when the site was downwind of the motorway to ensure that interference from other sources was minimal.

At North Shore, a daily pattern emerged of higher wind speeds during the day, and calmer conditions during the night. This was most evident in Period 5, shown in Figure 3.1, where the daily trend was quite pronounced. Discounting the last 12 hours of this period (as the wind direction measurements are not reliable at low speeds), the wind had a consistent westerly component. Wind speed and wind direction for all of the Auckland monitoring periods are shown in section V.1 of *Appendix V*.

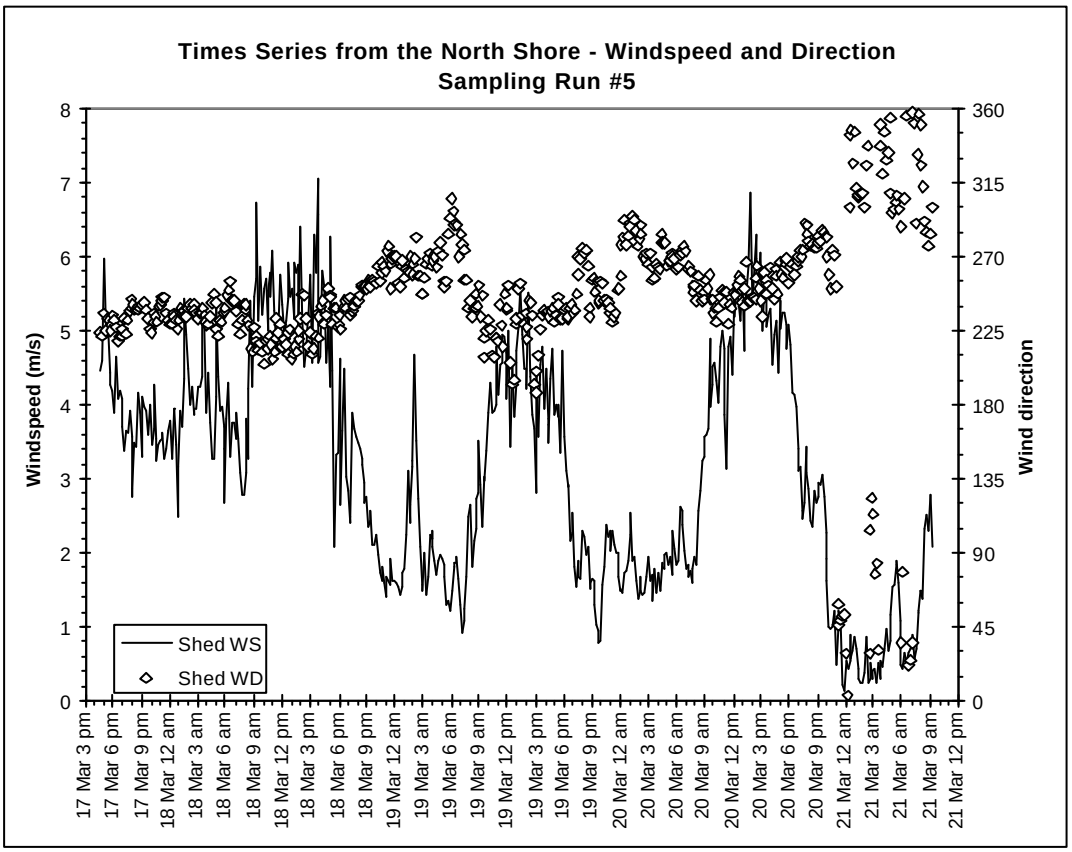

Figure 3.1 Wind speed and wind direction for North Shore Period 5 showing a consistent westerly trend (note for wind direction: 360°=N, 270°=W, 180°=S, 90°=E)

Carbon monoxide concentrations also demonstrated a daily pattern with sharp morning peaks, lasting from 06:00 to 09:00 (sometimes beginning before this time). The maximum concentrations recorded were between 4.5ppm and 8ppm at the sensor nearest the roadway. Elevated concentrations also occurred in the afternoons, not reaching as high a level as in the morning peaks but persisting for longer durations. Generally the afternoon peaks lasted from 15:00 into the evening, only to decrease to zero late at night. The recorded concentrations for Period 5 are shown in Figure 3.2, with the results for all monitoring periods available in section V.1 of Appendix V.

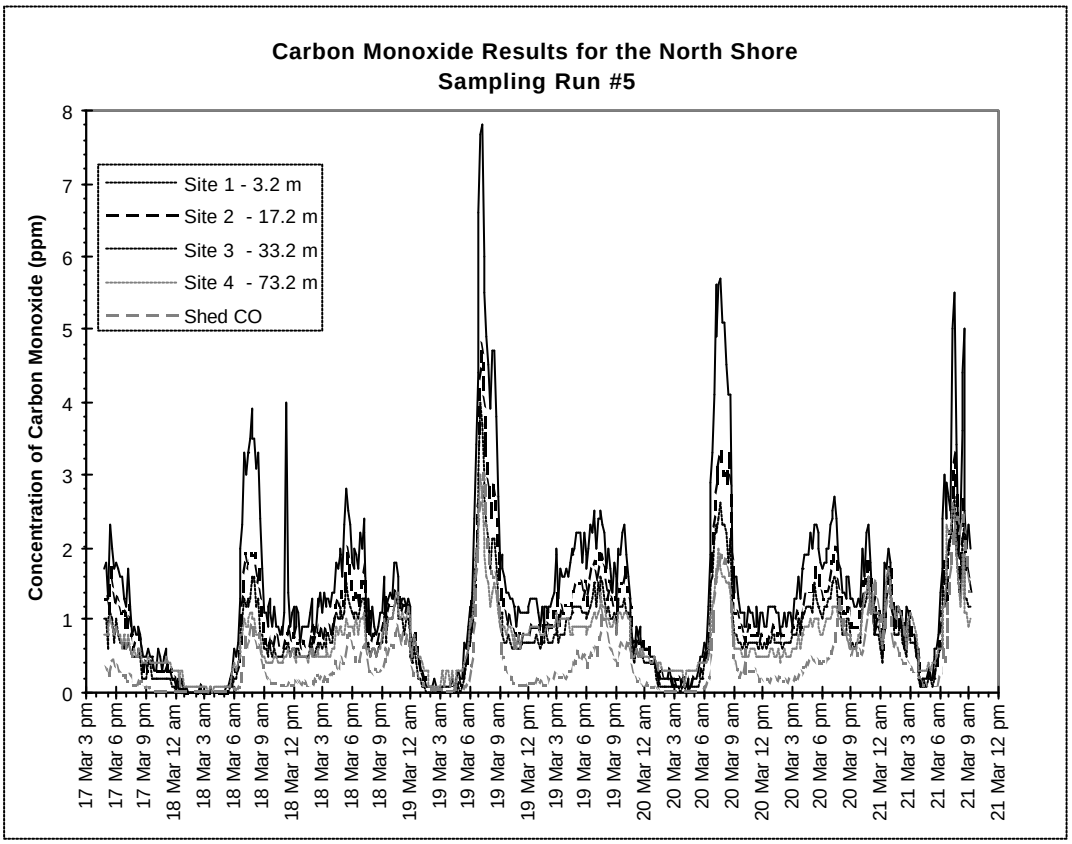

Figure 3.2 Carbon monoxide measurements for North Shore Period 5 showing the daily trend of sharp morning and broad afternoon peaks

The daily pattern in the carbon monoxide concentration mirrored the traffic flow rates, which had corresponding sharp peaks for morning rush traffic and flatter / broader peaks during the afternoon and evening. In addition, the numbers also reflected the changes in wind speed as concentrations were higher during the early morning when the wind speed was low, but suddenly decreased as the wind speed increased and day-time weather conditions commenced. This change occurred before the end of the morning rush of traffic into Auckland.

Looking at the concentration profile with distance from the source, concentrations at site 1 were significantly higher than the other sites (whose concentrations were quite similar to each other despite the additional distance between them). Also, at these sites further from the motorway the

carbon monoxide concentrations did not necessarily decrease with distance. This was expected because carbon monoxide disperses in the day-time convective atmosphere in all directions, becoming more diluted further away from its source. Consequently, contributions from other sources (e.g. traffic from nearby Wairau Road) can become more apparent with distance from the motorway, affecting the relative magnitudes of the carbon monoxide concentration measured at sensors 3, 4, and 5 and the analyser. During the evenings, the concentrations measured at each site were closer as the air was more stable, dispersion was reduced, and concentrations were less diluted with distance from the main roadway.

3.2.2 CO Results for Ngauranga Gorge - Wellington

Carbon monoxide was monitored for three periods comprising one "short" period (running for three weekdays continuously) and two "extended" periods (running for 23 and 17 days continuously) at the Ngauranga Gorge site between 29 April and 14 June 1997.

Meteorological data for the Ngauranga Gorge exhibited fundamentally different features from those of North Shore. Firstly, the channelling effect of the gorge restricted the wind to directions almost parallel to the road, either from the north-west (315°) or the south-east (135°). This is shown for the Period 1 of the monitoring in Figure 3.3 and was similar for other periods (see section V.2 of *Appendix V*). Secondly, the daily signature in wind speed was not so strong, with the wind being variable from day to day due to general changes in the weather conditions.

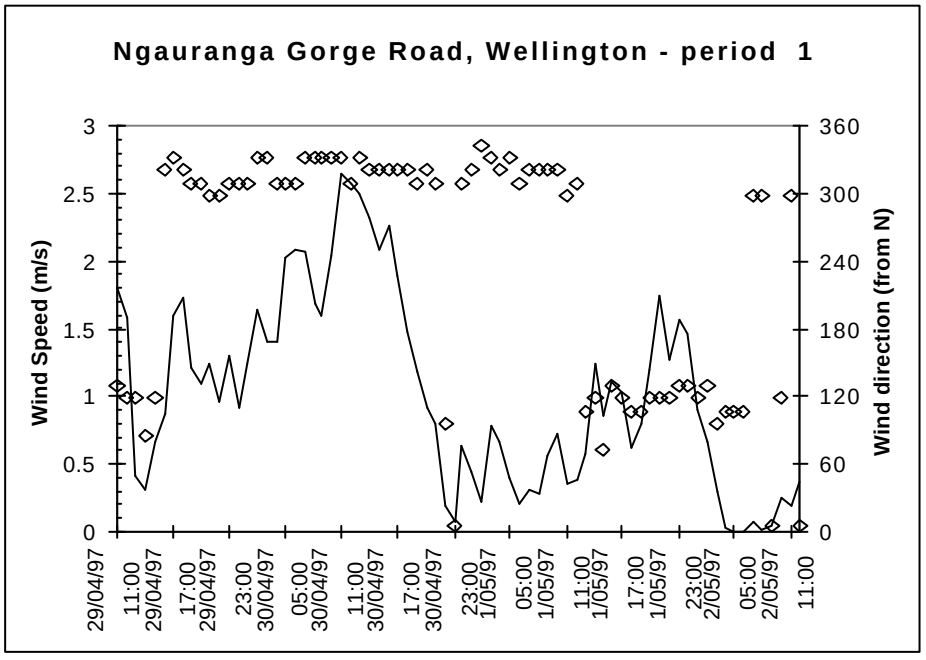

Figure 3.3 Wind speed and wind direction for Ngauranga Gorge Period 1 showing wind-channelling in direction but a reduced diurnal pattern in speed (note for wind direction: 360°=N, 270°=W, 180°=S, 90°=E)

Carbon monoxide sensor data relating to the same monitoring period are shown in Figure 3.4. Maximum concentrations of up to 10ppm were observed, and significant levels were measured throughout each day, as opposed to the sharp narrow peaks seen at North Shore. Concentrations followed a pattern with time similar to that of the northwest-bound traffic counts (also known as "uphill"). This is the direction outward from Wellington city, and had a larger evening, rather than morning, traffic count. Traffic in the other direction ("downhill") was further from the field site, and thus contributed less to observed concentrations.

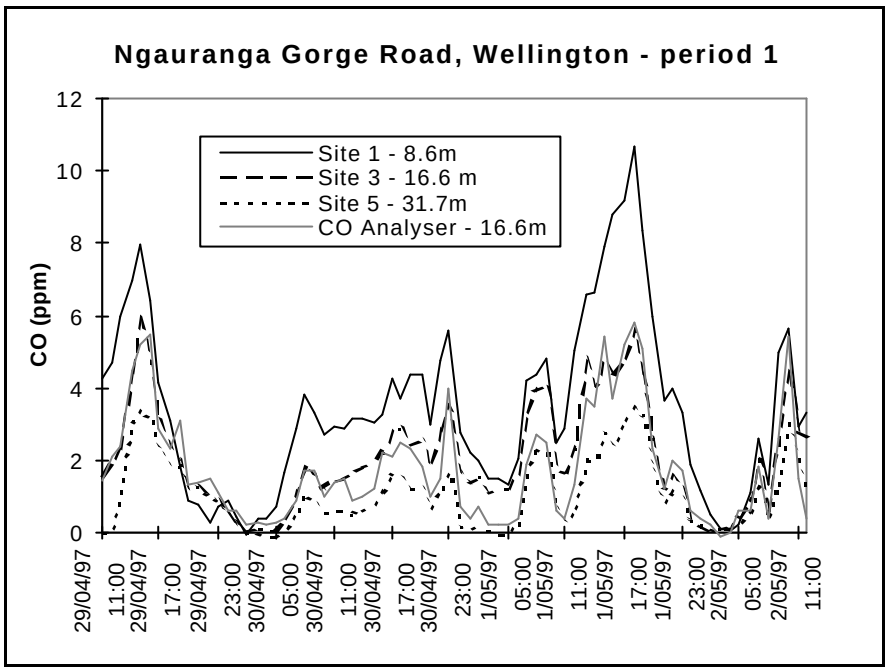

Figure 3.4 Carbon monoxide measurements for Ngauranga Gorge Period 1 showing the pronounced afternoon peaks

3.2.3 CO Results for Riccarton Road - Christchurch

Carbon monoxide was monitored for four periods at the Riccarton Road site between 8 May and 9 June 1997. Carbon monoxide and meteorological data from Week 2 are examined here, with essential features from the other times summarised. Results for all weekly periods are contained in section V.3 of *Appendix V*.

Each day in Week 2 showed a pattern of calm nights followed by light winds during the day (see Figure 3.5). This pattern is typical for Christchurch during night-time inversion conditions in winter. As the predominant wind direction was from the north, the sensors were located downwind of the roadway.

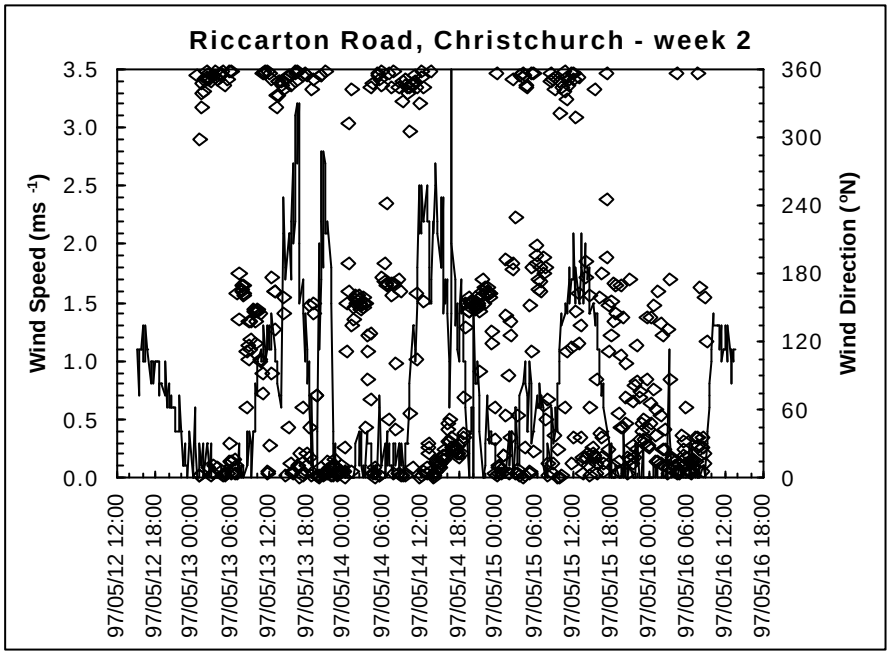

Figure 3.5 Wind speed and wind direction for Riccarton Road Week 2 showing calm nights and light winds during the day (note for wind direction: 360°=N, 270°=W, 180°=S, 90°=E)

The corresponding measurements of carbon monoxide (see Figure 3.6) demonstrated a strong relationship with both traffic counts and wind speed.

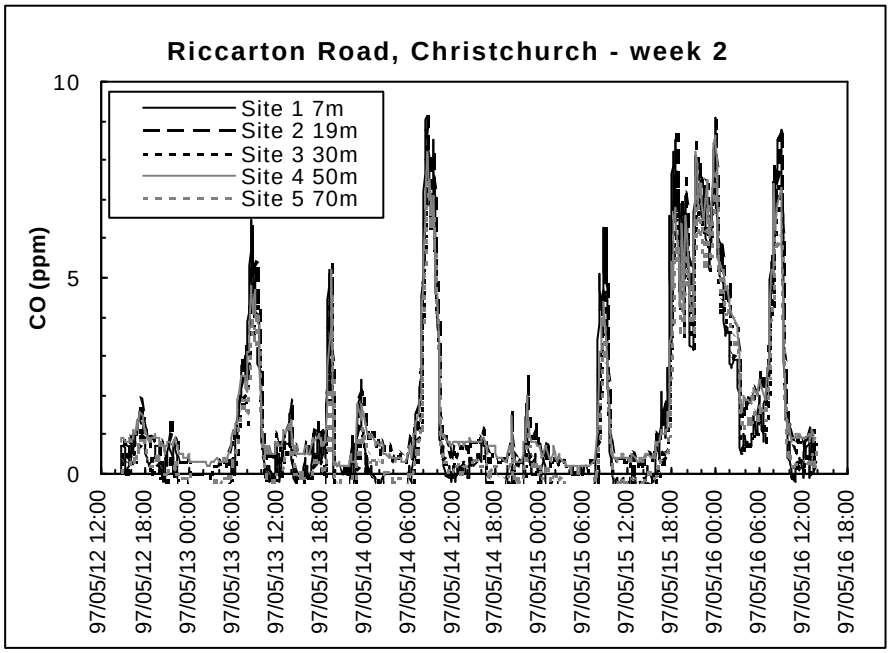

Figure 3.6 Carbon monoxide measurements for Riccarton Road Week 2 showing the effect of traffic and wind speed on the peaks

From about 06:00, the carbon monoxide increased with increasing traffic amounts in the calm conditions. Then, as the night-time inversion broke up, the air became more unstable and windier, rapidly diluting the concentrations until they were almost zero by about 10:00. This occurred in spite of the traffic remaining at constant levels throughout the day. Short-term peaks in carbon monoxide were associated with short calm wind periods. The exception to this was the period of elevated concentrations during the evening of 18 May 1997, which is addressed in section 3.3 on modelling results.

It is interesting to note that concentrations measured at each sensor were very close. In the case of the wind blowing from the north, this indicates that the air was very stable, with concentrations decreasing little with distance from the roadside. This was likely to occur in the morning after the traffic had built up but before the temperature inversion had dissipated, even when the wind speed was not high.

Other specific features arising from the monitoring in Christchurch include the following:

- Calm periods in the evening - after sunset, for example - lead to peaks of carbon monoxide concentrations, emitted by evening traffic.
- In weeks 3 and 4, one sensor was located 120m from Riccarton Road. At this distance from Riccarton Road, concentrations were higher than at sensors nearer the road, possibly indicating other local sources of carbon monoxide.
- In weeks 3 and 4, one sensor was located on the opposite side of Riccarton Road. In calm northerly conditions, concentrations were almost as high as at the main sites, indicating diffusion in all directions under weak wind conditions.
- Data from the analyser followed closely the concentrations obtained from the sensors, and early in June exhibited some relatively high values, reaching around 20ppm. Note the 1-hour air quality guideline is 24ppm (*MfE 1994*).

3.2.4 CO Concentration vs Distance

The change in monitored carbon monoxide concentration versus distance is shown in Figure 3.7 for two examples covering North Shore in Auckland and Riccarton Road in Christchurch.

Generally from the monitoring results, concentration decreased with distance but in a highly variable way. For example, some situations recorded a sharp drop during unstable day-time conditions (as seen in the 09:00 results for Figure 3.7a) whilst others produced a near plateau for stable night-time conditions (as seen in the 02:00 results for Figure 3.7a and the 18:00 results for Figure 3.7b). These actual results compare well with those expected from theory (see Figure 3.8) but are complicated by the fact that they represent variations in not only the stability (a measure of atmospheric mixing) but also the source strength (number of vehicles) and wind speeds during the day . In addition, the sharp increase in theoretical values near the source (rising to a constant value at the source origin) shows up clearly in Figure 3.8 but is not so clearly indicated in the monitored data as the first sensors were located too far away to pick up this gradient.

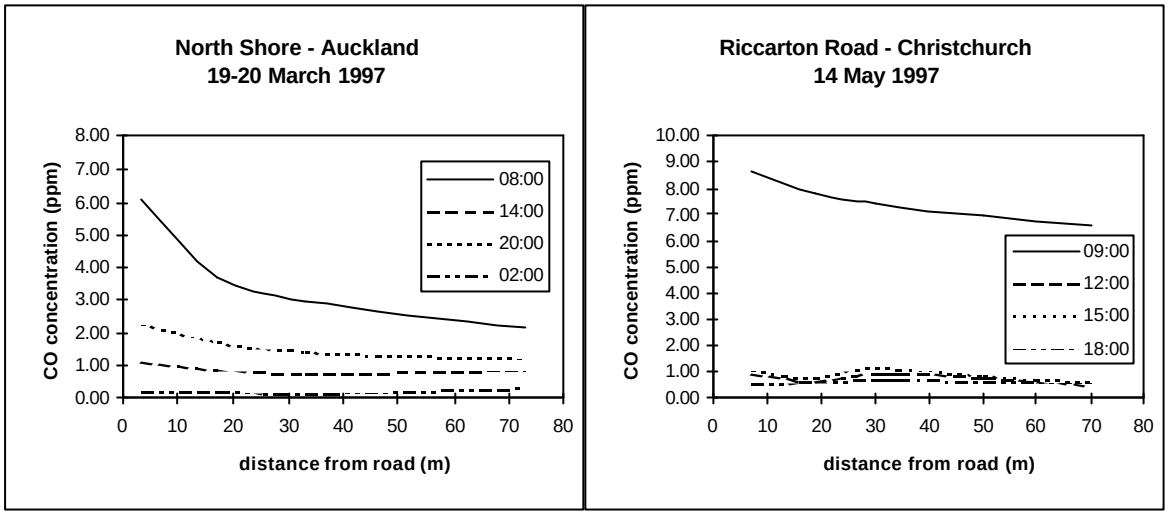

Figure 3.7 Monitored carbon monoxide concentration change vs distance for (a) North Shore example (b) Riccarton Road example

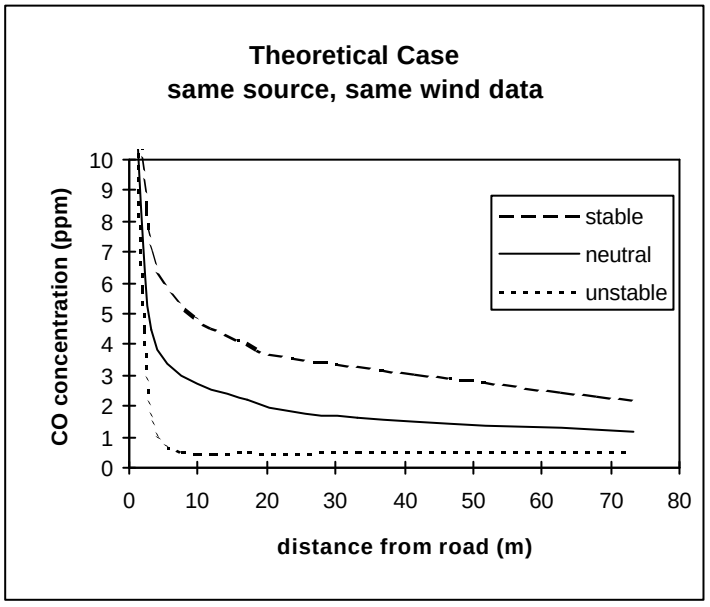

Figure 3.8 Theoretical carbon monoxide concentration change vs distance for the same source and wind data showing the effect of stability

Overall the carbon monoxide concentration profile with distance depends on a number of factors outlined in the following table (Table 3.9).

Previous monitoring work (*Nichol et al 1997*) attempted to assess these relationships but failed to demonstrate strong correlations (see Figure 3.9) as it was not possible to look at the variables in isolation.

Table 3.9 Factors affecting carbon monoxide concentration profile with distance

Factor Type	Variable
source strength	• vehicle numbers • emission factors*
wind data	• wind speed • wind direction
atmospheric stability	• stability class • mixing height
site characteristics	• terrain • traffic configuration • proximity of buildings

* emission factors are a function of vehicle speed and road type

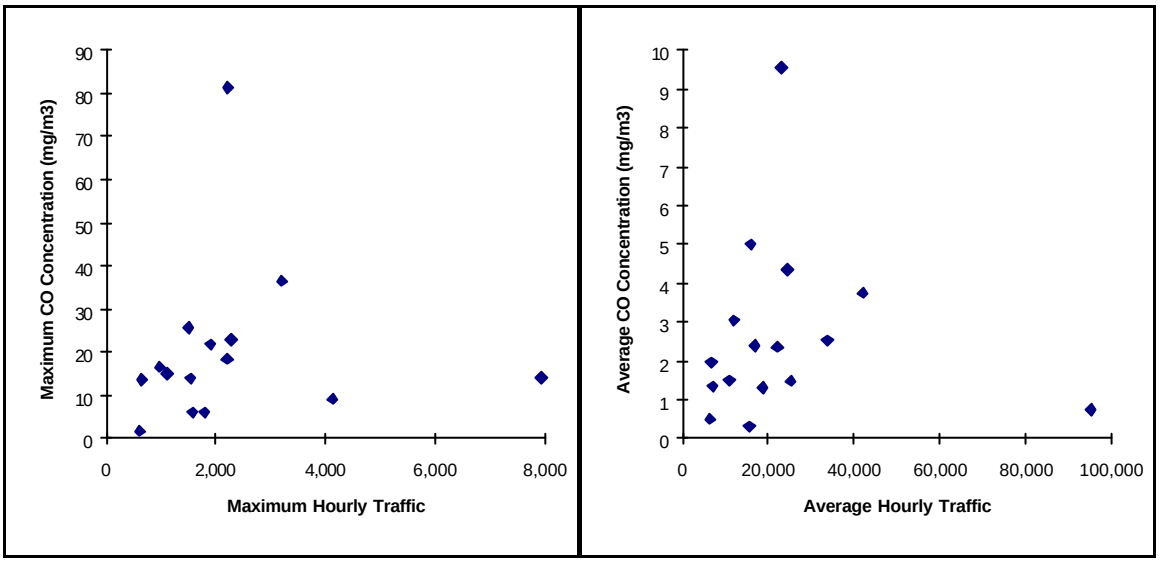

Figure 3.9 Relationship between carbon monoxide and average traffic counts in a number of New Zealand locations
(a) maximum concentration (b) average concentration

In this study, the application of CAL3QHC (discussed in the next section 3.3) was more sophisticated and provided the opportunity for the effect of all these factors to be quantified.

3.3 CO Modelling

For the carbon monoxide modelling component, the overall objectives were:

- to explain observed pollution levels due to motor vehicles and their magnitudes as functions of distance from the roadside
- to provide guidance in the use of the whole modelling system in future applications

For this, careful choice of input parameters was required, and the choice was generalised so that the model reproduced well as many cases as possible. During the course of this selection process, the relationships between motor vehicle emissions, meteorology and measured carbon monoxide concentrations were established and these are explained in more detail in the following sections. For more information on the input required for the modelling, a summary is provided in section 2.4 previously and covered in more detail with actual sample input files in *Appendix VI.*

In addition, the model had to be modified to cope with situations involving low wind speeds where the actual measurements of both wind speed and direction become unreliable. Since low wind speeds can be associated with high pollution events, the modifications were important for predicting concentrations accurately. Consequently, additional work was put into deriving "default" model inputs for cases of low wind speed - by deciding a suitable wind speed (at least 1 m/s), wind direction (more difficult as direction data is not reliable at low speeds), and an appropriate stability class (a measure of the tendency of the surrounding air to mix) - in order to reproduce observed carbon monoxide concentrations.

In general, the monitoring in Auckland was carried out in higher winds, whereas at the other sites, calm conditions were often experienced. As a result, the following steps were used to develop logically the application of CAL3QHC to the monitoring data:

1. Initially, CAL3QHC was applied to the Auckland - North Shore monitoring data to achieve as good a fit as possible of model to observations for normal to high winds.
2. CAL3QHC was then applied to the Wellington - Ngauranga Gorge monitoring data to derive the default inputs suitable for calm conditions and to achieve a fit consistent with that achieved for Auckland.
3. Finally, the modified modelling system was tested on the Christchurch - Riccarton Road monitoring data to validate the process.

Modelling was performed for all monitoring periods at all sites (see *Appendix VII*) and is discussed in detail for specific cases for each site as follows.

3.3.1 Modelling CO at North Shore - Auckland

The Auckland case selected for discussion relates to Period 5 of the North Shore monitoring, where CAL3QHC was applied to data collected between 17:00 on 17 March 1997 to 09:00 on

21 March 1997. All data were averaged to cover 1 hour periods - appropriate to the carbon monoxide air quality guideline (*MfE 1994)* - to make a total of 88 hours of results for this case.

5.5.2.1 Input Data

The model area consisted of a 2km long stretch of State Highway 1 (SH1), plus a part of Wairau Road (WR) alongside. The northbound section of SH1, the southbound section of SH1, and WR with both directions taken together were all 16m wide - comprising 10m of road and 6m of "mixing zone" due to the turbulent wake of moving traffic. Each carriageway of SH1 and WR was divided into three links. Model receptors were located at the horizontal positions of the carbon monoxide sensors, at a vertical height of 1.7m (except for the shed analyser, whose intake was at a height of 3.2m). The road links and model receptor locations (corresponding to the sensor locations) are plotted in Figure 3.10.

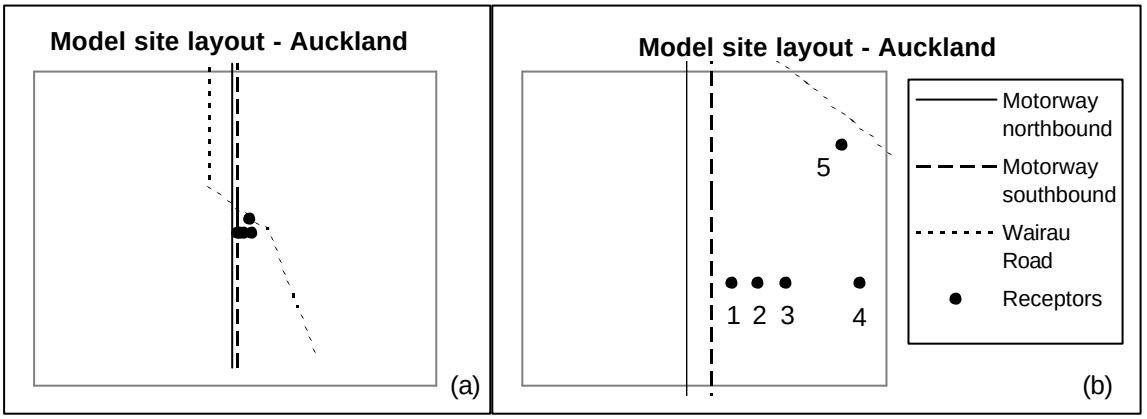

Figure 3.10 Site layout for the Auckland case
(a) 2km x 2km (b) 200m x 200m

Wind speed and wind direction were measured at the shed at a height of 10m, at receptor location 5, and the data for Period 5 are shown in Figure 3.11. The measured wind speed from the 10m mast was converted to a value for 1.7m by multiplying by a scale factor of 0.69 (which assumes that wind speed varies logarithmically with height). In this case as wind direction measurements are unreliable at wind speeds below 1 m/s and CAL3QHC cannot handle these low speeds either, the last few hours of measurements were discounted (which is standard modelling practice). Modelling cases covering calm winds are discussed later in detail for the Wellington and Christchurch cases.

The stability class was another important input to the model as it gives a measure the spread or mixing of pollutants in directions other than the wind direction (that is, transversely and vertically), and is classified from A (unstable) to F (stable). It was estimated according to criteria devised by Pasquill (*Pasquill and Smith 1983, p336*), where weak winds give class A (unstable) during the day, and class F (stable) at night. Strongest winds give class D (neutral) day or night. In the Auckland case, dawn occurred between 07:00-0800 and dusk between 17:00-18:00, and these periods were designated class D.

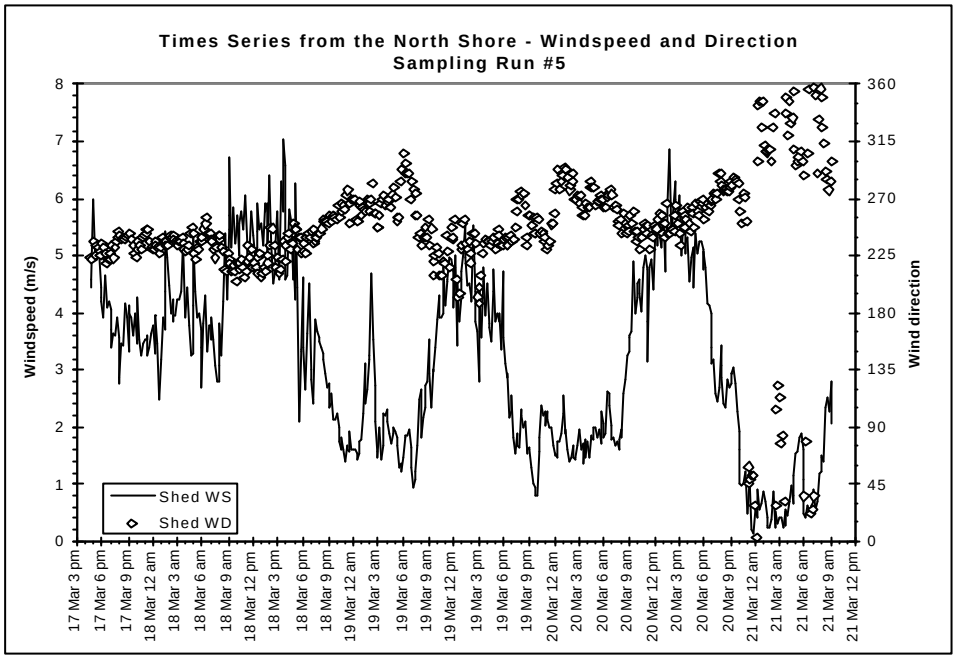

Figure 3.11 Wind speed and wind direction for the Auckland case

Traffic count values were taken from a week's data, averaged for each hour over the five weekdays. Counts from sites on the northern and southern WR links were very similar and were averaged to give counts for the middle link. The traffic counts used are shown in Figure 3.12 (see *Appendix IV* for further details).

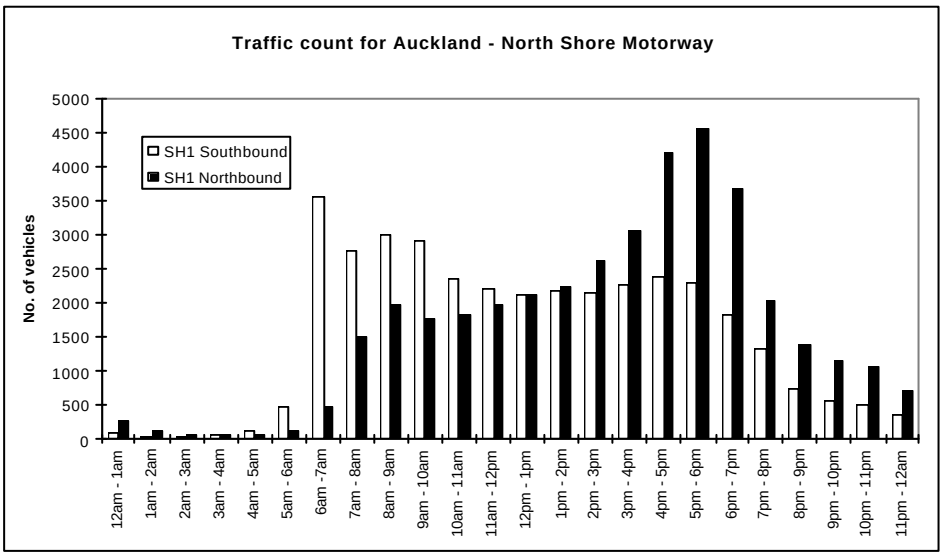

Figure 3.12 Traffic counts for the Auckland case

The number of vehicles on SH1 exhibited well-defined morning and evening peaks, whereas traffic along WR was fairly uniform throughout the day. Contributions to carbon monoxide from

WR were negligible as most of the sensors were closer to SH1, and the monitoring was undertaken when the wind was generally westerly (270°). SH1 was considered congested southbound from 06:00 to 10:00, interrupted northbound from 16:00 to 19:00, and free flowing the rest of the time. WR was considered congested all of the time, as the portion of road near the site included an intersection controlled by traffic lights. Emission factors were chosen based on these considerations and are summarised in section 3.1.4.

5.5.2.2 Model Results

Figure 3.13 shows the comparisons of the modelled versus observed concentrations at receptors 1 and 5 for the Auckland case using the previous input. Model results compared well with field observations, with the temporal trends in carbon monoxide - particularly the sharp morning peaks and flatter afternoon peaks - being reproduced by the model.

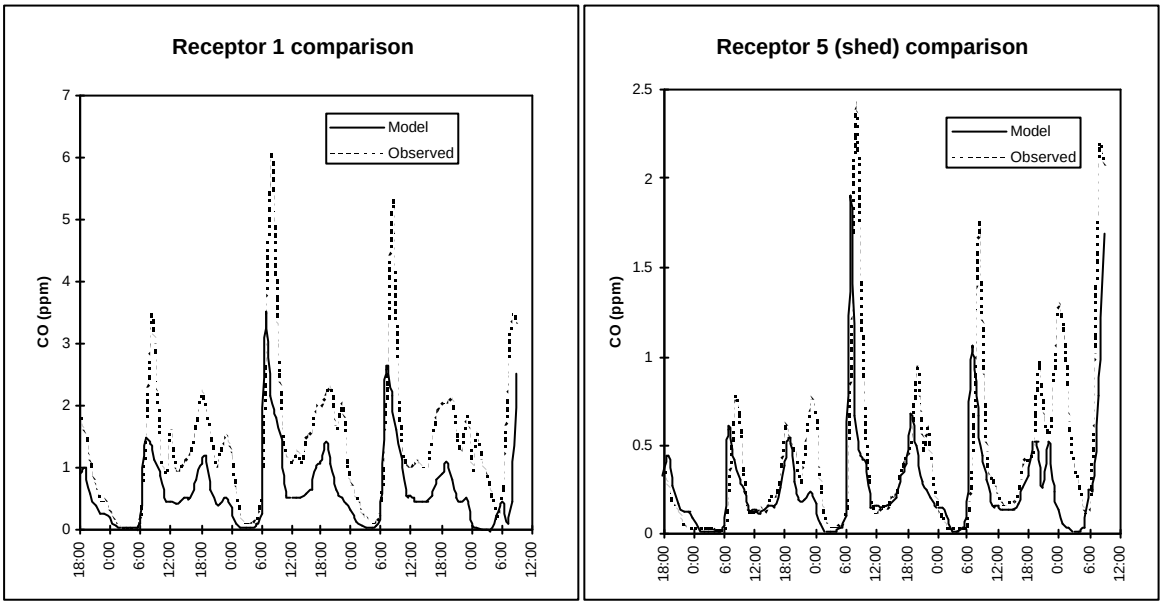

Figure 3.13 Comparison between modelled and observed results for the Auckland case

Although the model under-predicted the absolute values of the observations by an average factor of about 1.7, this is well within the acceptable bounds for pollution dispersion modelling (where modelling results within a factor of 2 are considered good). This under-prediction factor was similar for each receptor location, which demonstrated that the model captured well the distribution of carbon monoxide with distance from the highway. Possible explanations for this under-prediction are discussed later in section 3.3.5.

3.3.2 Modelling CO at Ngauranga Gorge - Wellington

The Wellington case selected for discussion relates to Period 1 of the Ngauranga Gorge monitoring, where CAL3QHC was applied to data collected between 13:00 on 29 April 1997 to 12:00 on 2 May 1997. All data were averaged to cover 1 hour periods - appropriate to the carbon monoxide air quality guideline (*MfE 1994*) - to make a total of 71 hours of results for this case.

The Ngauranga Gorge Road (NGR) is a similar highway to SH1 in Auckland, and, with respect to the model/observations comparison was expected to produce similar results to the Auckland case. Slight differences existed due to higher emissions factors for free flowing traffic uphill, and the effect of the gorge in channelling the wind parallel to the road. Dispersion was possibly affected too, but the CAL3QHC model does not include topographic or canyon effects (however these would have been minimal for NGR as the actual road was quite wide). The main modelling challenge to overcome for the Wellington case was how to deal with the situations of calm conditions, which arose during the field campaign at Ngauranga Gorge.

5.5.3.1 Input Data

The model area consisted of a 2km long section of NGR, divided into eight links - four in each direction - each 16m wide. Three model receptors were located at the same horizontal distance from the road as the sensors 1, 3 and 5 and at a vertical height of 1.7m. The road links and model receptor locations are shown in Figure 3.14.

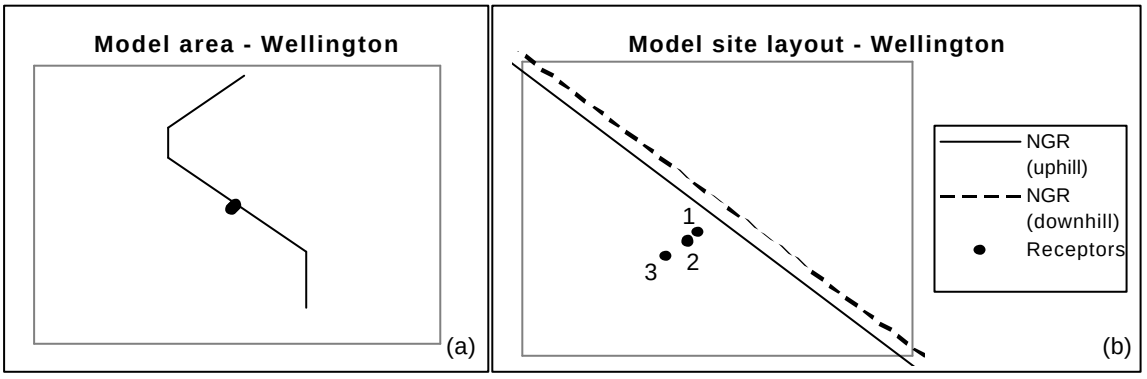

Figure 3.14 Site layout for the Wellington case
(a) 2km x 2km (b) 200m x 200m

Wind speed and wind direction were measured at the pumping station at a height of 3.4m, at receptor location 2, and the data for Period 1 are shown in Figure 3.15. For most of this period, the wind direction was either 135° or 315°, in directions parallel to the highway. Measured wind speeds were adjusted from 3.4m to sensor level at 1.7m, by multiplying by a factor of 0.85. Taking model limitations (CAL3QHC handles a minimum wind speed of 1 m/s) and equipment limitations (the anemometer used had a start-up speed of 0.75m/s), any measured wind speeds less than 1 m/s - and their associated wind directions - were not considered reliable. In order to give a consistent carbon monoxide concentration, a default wind speed and wind direction was

chosen for these calm events. Examination of peak hour concentrations suggested that the best results would be obtained with a default wind speed of 1 m/s and a default wind direction of 330° (which was 45° to the highway).

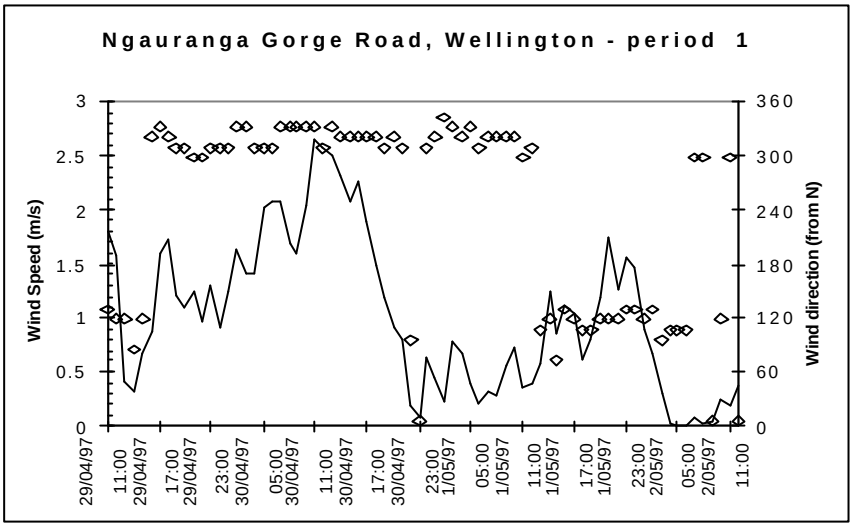

Figure 3.15 Wind speed and wind direction for the Wellington case

For the stability at the Wellington site, conditions were generally hazy at the time of the field work, so the unstable classes (A, B or C) were not possible as these require sunlight for mixing. The same night-time stable classes (E and F) were applicable as in Auckland, but neutral class D was applied to an extended day-time period from 08:00 to 18:00.

Traffic counts were developed for NGR using the same method as in Auckland and are shown in Figure 3.16 (see *Appendix IV* for further details).

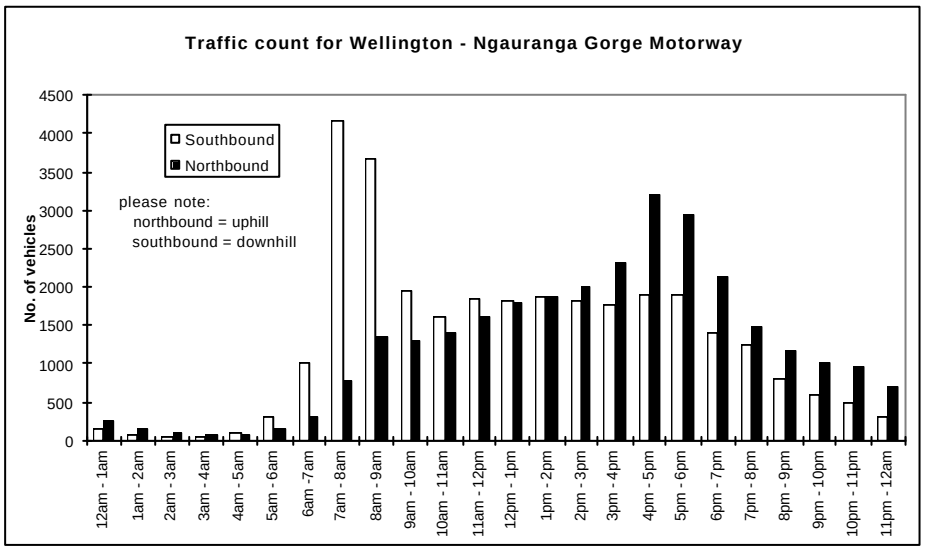

Figure 3.16 Traffic counts for the Wellington case

Here as in the Auckland case, morning and evening peak times were well-defined. The uphill carriageway was congested from 15:00 to 18:00, and interrupted flow occurred from 12:00 to 15:00 and 18:00 to 19:00. In the downhill direction, traffic flow was congested from 07:00 to 09:00, and interrupted from 09:00 through to 18:00. At other times, the traffic was assumed to be freeflowing. The emission factors corresponding to these assumptions are summarised in section 3.1.4.

5.5.3.2 Model Results

Figure 3.17 shows the comparisons of the modelled versus the observed concentrations at receptors 1, 2 and 3 (corresponding to sensor positions 1, 3 and 5) for the Wellington case using the previous input.

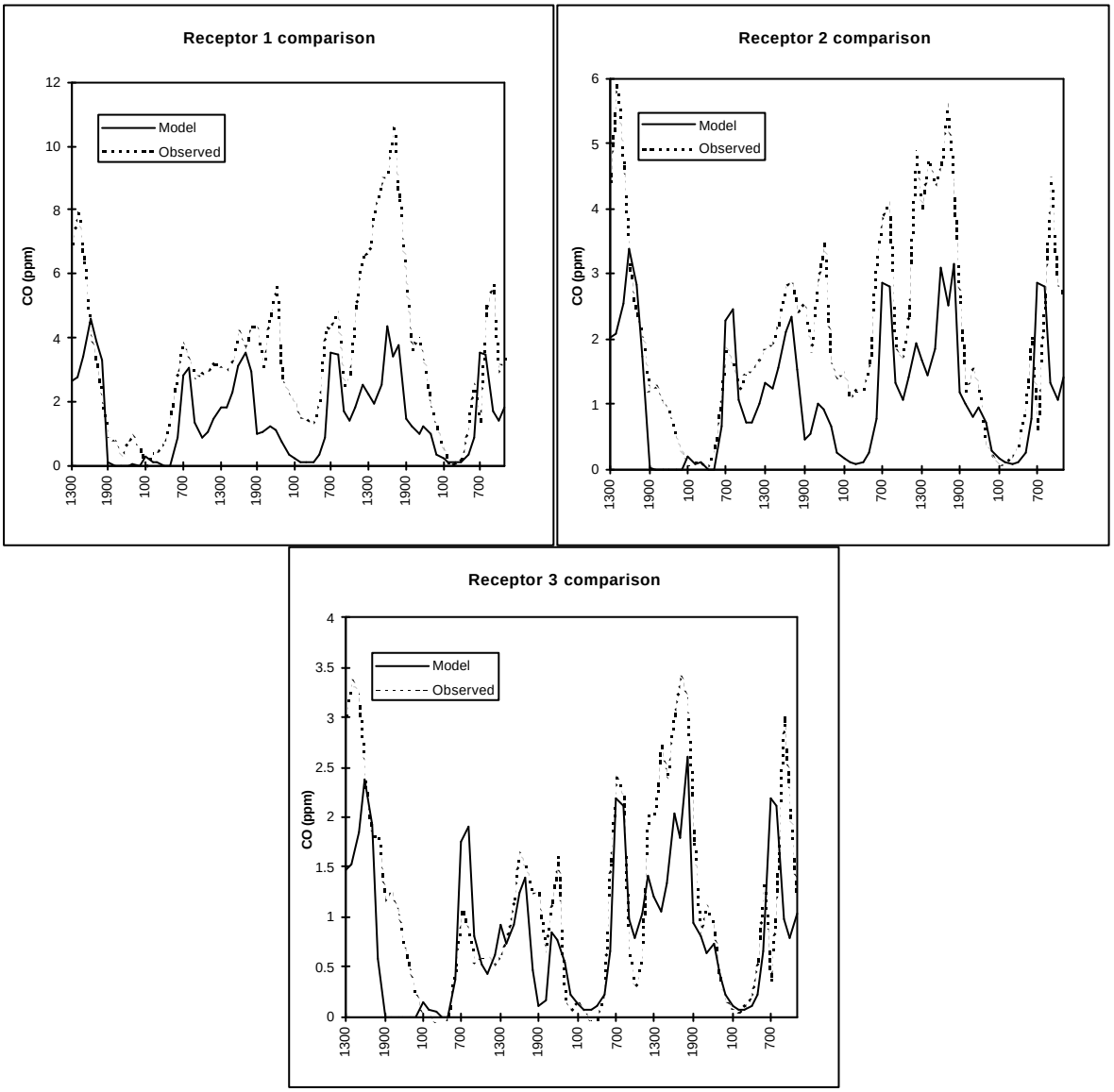

Figure 3.17 Comparison between modelled and observed results for the Wellington case

Again, the model under-estimated the concentrations, but the trends in time were well-captured. On average, the ratios of observed concentrations to modelled concentrations were 1.8, 1.5 and 1.2 for receptors 1, 2, and 3 respectively (see section 3.3.5 for further discussion). All were satisfactory by dispersion modelling standards, although the trend in ratios suggests that some non-neutral stability should have been compensated for during the day-time. Overall however, the modified model performed as well for the Wellington case as it did for Auckland which confirmed the choice of the default inputs developed for calm conditions.

3.3.3 Modelling CO at Riccarton Road - Christchurch

The Christchurch case used to validate the modified model was Week 2 of the Riccarton Road monitoring with data from 15:00 on 12 May to 13:00 on 16 May 1997. All data were averaged to cover 1 hour periods - appropriate to the carbon monoxide air quality guideline (*MfE 1994*) - to make a total of 94 hours of results for this case.

The Riccarton Road (RR) site covered a busy central urban roadway located in central Christchurch. Week 2 was subject to frequent calm periods during the monitoring and was considered a good test of the applicability of the defaults developed in the modified CAL3QHC model from the NGR data in Wellington.

5.5.4.1 Input Data

The model area consisted of RR and all nearby streets for which traffic count data were available, although contributions to the modelled carbon monoxide from streets other than RR were considered minor. Eight links were selected where each link of n lanes had a corresponding width $3n+6$ metres. Model receptors were located at the horizontal positions of the carbon monoxide sensors (7m, 19m, 30m, 50m and 70m south of RR) and at a vertical height of 1.7m. The road links and model receptor locations used are shown in Figure 3.18.

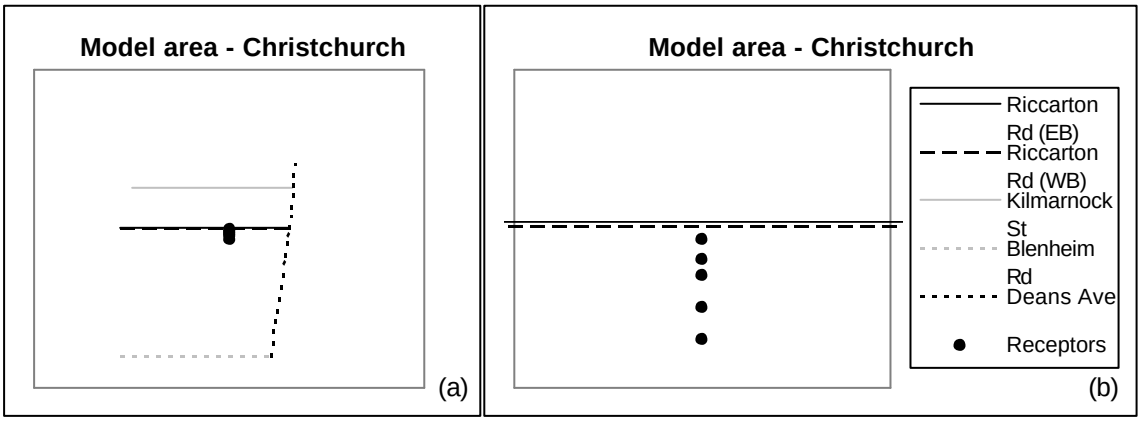

Figure 3.18 Site layout for the Christchurch case
(a) 2km x 2km (b) 200m x 200m

Wind speed and wind direction were measured at the same height as the sensors , at receptor location 3, so no scaling was required for these numbers. Data for Week 2 are shown in Figure 3.19.

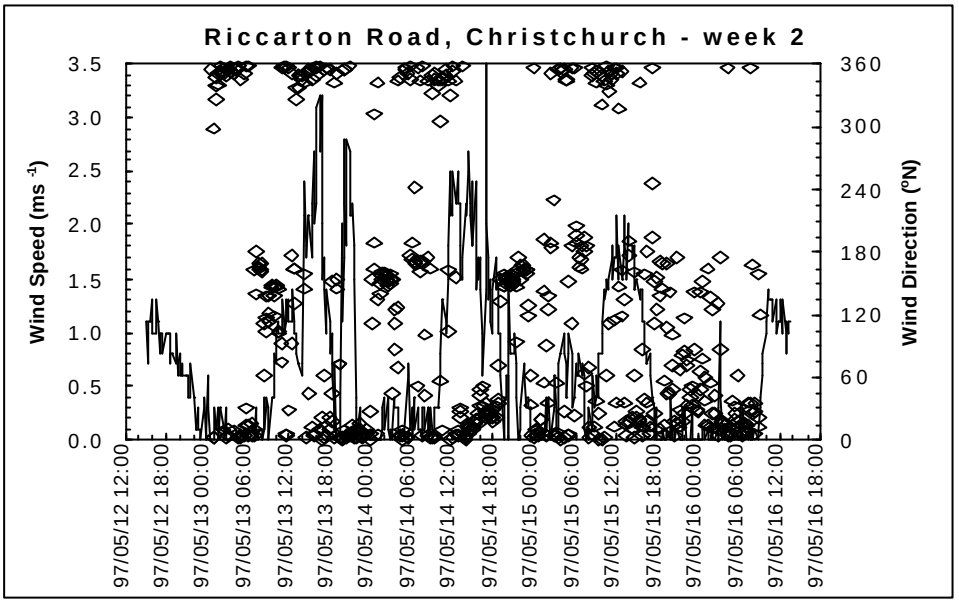

Figure 3.19 Wind speed and wind direction for the Christchurch case

Each day in this period followed a similar pattern of calm overnight, followed by light winds during the day-time. Direction was from the north mainly (at 0°), with some southerly winds (at 180°). The buildings nearby seemed to have caused some channelling effect on the wind because of the consistent and opposite directions recorded. To compensate for the frequent instances when the measured wind speeds dropped to low levels, a lower limit of 1 m/s for wind speed with a corresponding wind direction of 45° was imposed for the modelling.

Additional care was required when applying the modified model to Christchurch, as the morning traffic peak hour occurred regularly during the calm period. Feedback from the monitoring was used to help determine the appropriate stability classes to apply. Measured concentrations did not decrease rapidly with distance from the roadside, which tends to occur in stable conditions when the wind has a component perpendicular to the road link. Consequently, in these near-winter conditions the break-up of the night-time inversion was delayed and pollution near the surface prevented the penetration of sunlight to increase the mixing. This created the unusual circumstance where the model should use a stable class even after the sun had actually risen. Hence sunrise in the model was delayed until the hour 09:00-10:00.

The weekday-averaged hourly traffic counts used for RR are shown in Figure 3.20. Riccarton Road recorded quite a different traffic profile from the two motorway sites in Auckland and Wellington. The number of motor vehicles grew between 05:00 and 09:00, and remained at the 09:00 level for the rest of the day (apart from a small decrease between 09:00 and 10:00). Surrounding roads included in the model runs also exhibited a similar pattern.. From the traffic

data, congested conditions were assumed eastbound from 08:00 to 18:00, and from 08:00 to 19:00 westbound. Interrupted flow was assigned to the adjacent periods of 07:00 to 08:00 and in the evening until 21:00, otherwise the traffic was considered free-flowing. Emission factors were chosen based on these considerations and are summarised in section 3.1.4. It should be noted however that these factors were based on the "central urban" road type rather than the "motorway" road type (used in the Auckland and Wellington cases) and the emission rates were approximately double those used for the other two sites.

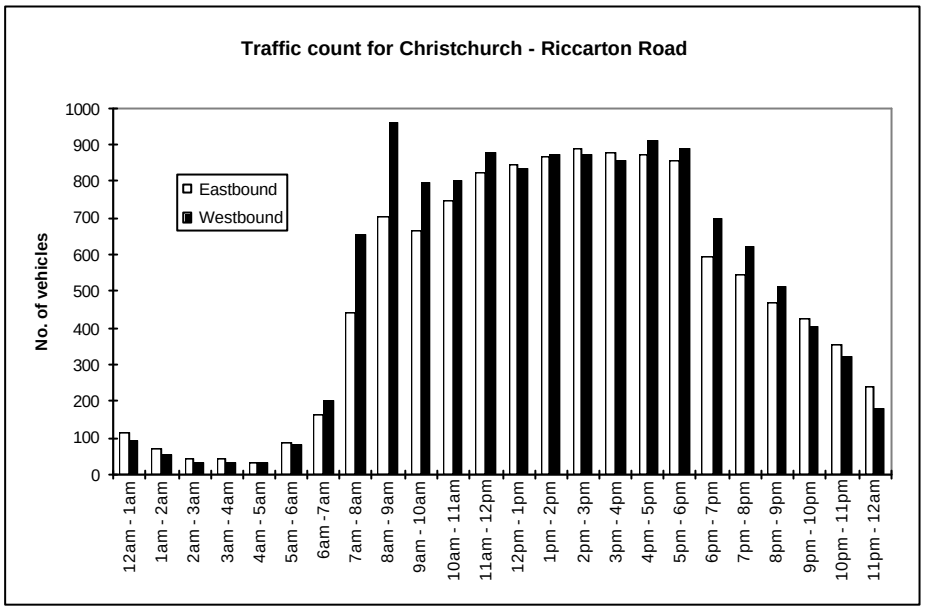

Figure 3.20 Traffic counts for the Christchurch case

5.5.4.2 Model Results

Figure 3.21 shows the comparisons of the modelled versus the observed concentrations at receptors 1 and 4 for the Christchurch case using the previous input.

Once again, the model reproduced the measurements well, with regard to the magnitudes and decreases in concentrations with distance from the road. Observed concentrations did not decrease significantly with distance, and the modelled decrease was kept to a minimum. Due to the default wind speed values used for calm conditions, and the fact that the same traffic counts (averaged) were used for each day, the model peak at 09:00 was identical for each day, whereas in reality day-to-day variability was seen in the observed concentrations. This difference was less likely to be a feature of differing daily traffic counts as more likely to be caused by variations in the actual wind conditions. The concentrations were very sensitive to wind direction (see section 3.3.4 on model sensitivities), which could not be measured reliably during the calm periods. The default wind was chosen so that the model produced concentrations within a factor of 2 of the observed concentrations to match the results of the other two sites.

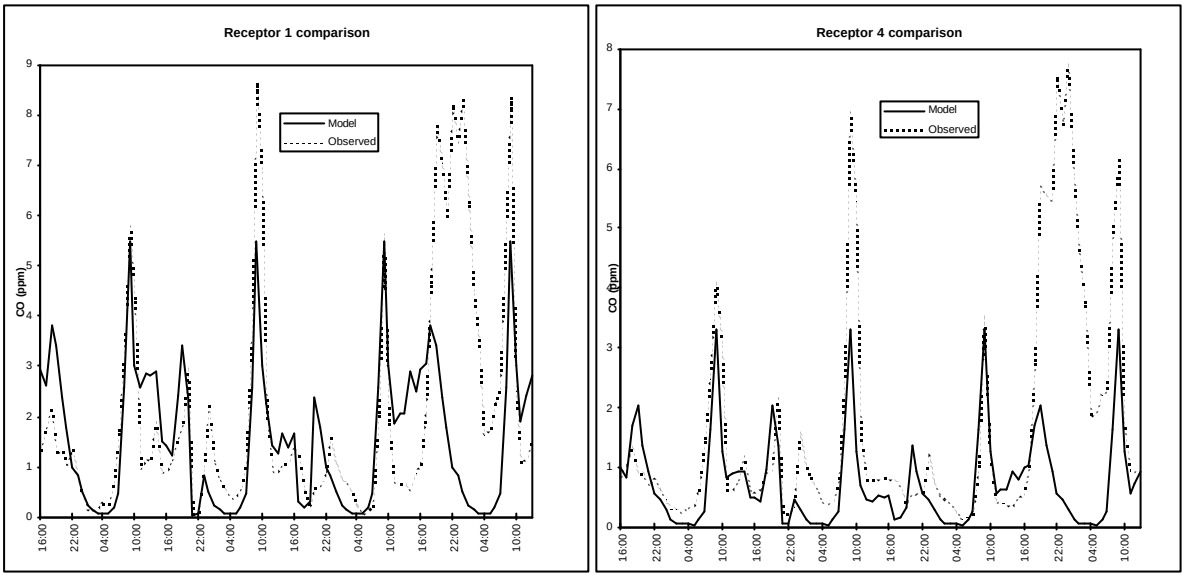

Figure 3.21 Comparison between modelled and observed results for the Christchurch case

It is notable that the carbon monoxide levels measured during the final evening of the period were not reproduced by the model. It is not known how such high concentrations arose, the main possibilities being:

- contribution from other sources such as solid fuel heating
- a "one-off" event in the city which lead to extraordinarily high traffic volumes
- an unusually shallow inversion layer trapping and concentrating the carbon monoxide
- a wind speed that was extremely small.

3.3.4 Sensitivity of CAL3QHC Model

Many input parameters are required for CAL3QHC, and the concentrations produced have varying degrees of sensitivity to these. The most important ones are wind data, stability class, traffic counts, and emission factors.

Results depend on the latter two source parameters in a simple manner, where, as should be expected, carbon monoxide concentration is proportional to both of these. However, the relationship with the meteorological parameters is more complex. Dispersion of pollutants has components parallel to and perpendicular to the wind, so the highest concentrations measured at sensors can occur when the wind is in any direction - therefore all directions should be taken into account. Also as wind speed decreases, concentrations may be expected to rise but a decrease in wind speed during the day can lead to more vertical dispersion and result in falling concentrations.

These anomalies can be reproduced in the model by performing "idealised" model runs, such as allowing the stability class to be a function of wind speed.

Consider a single roadway, 1km long, and 16m wide, assigned arbitrary traffic counts and emission factors. With a wind speed of 3m/s, the stability class can be between B (unstable, day-time) and F (stable, clear night). The road is aligned east-west, and the receptor distance is in the northward direction; hence a wind direction 180° is perpendicular to the road, from road to receptor location, 90° is parallel to the road, and less than 90° is in a direction from receptor to road (as shown in Figure 3.22).

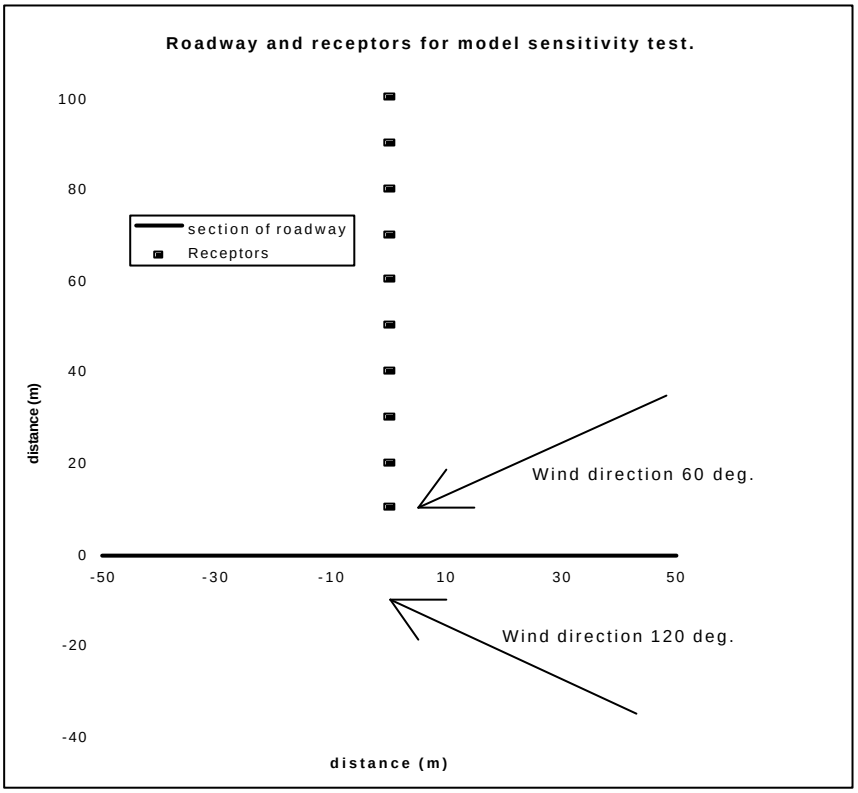

Figure 3.22 Roadway and receptor configuration for the CAL3QHC sensitivity test showing wind direction vectors

Relative carbon monoxide concentrations for different wind directions, and for distances up to 100m from the road, are plotted in Figure 3.23. In the unstable case (class B), for distances close to the roadway the wind direction of maximum concentration is 105° but for distances of more than 20m concentrations are very similar for all wind directions between 105° and 180°. This is due to the spread of pollutants in directions other than the wind direction itself, and results in appreciable concentrations close to the road even when the wind direction is 60°.

In contrast, for the stable case (class F), there is far less diffusion in directions other than the wind direction. Hence concentrations are zero if the wind direction is less than 90° (note the 60° results are actually on the x-axis) and for 180°, the concentration does not drop with distance so rapidly. For directions between these the concentrations are far higher near the road than in the unstable case (class B), as there is a contribution from traffic at greater distances from the receptors. Also note that concentrations are far more sensitive to wind direction in the stable case than in the unstable case.

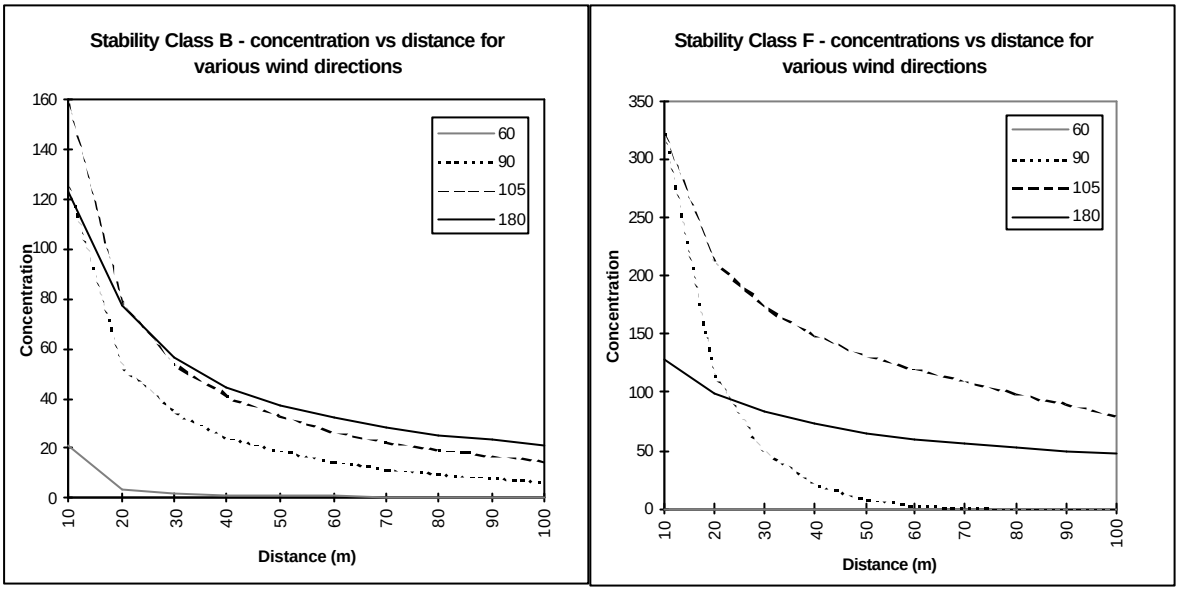

Figure 3.23 Sensitivity of CAL3QHC to wind direction and stability class

Halving the wind speed doubles the concentrations in the stable case, and almost doubles them in the unstable case (this is not exact, since in the unstable case, diffusion is also playing a part). However, the converse is not true. Doubling the wind speed to 6m/s changes the stability completely. In this case, a neutral stability (class D) must be used as the higher winds inhibit convection during the day (which makes the day-time unstable flows more stable) and cause shear instability and gravity waves at night (which destabilise the stable night-time flows). For this doubled wind speed, the resulting concentrations are close to those from the unstable case (class B), and between one-fifth and one-third of the those from the stable case (class F). Other parameters, such as surface roughness, mixing height, and the presence of other roads have only a small effect on the modelled carbon monoxide concentrations.

In summary, CAL3QHC is sensitive to various input parameters as shown in Table 3.10.

Table 3.10 Summary of the sensitivity of CAL3QHC to various input parameters

Input Parameter	Effect
Vehicle Numbers *Emission Factors*	proportional
*Mixing Height** *Surface Roughness*	insensitive
Wind Direction *Wind Speed* *Stability*	complex relationships as described in the idealised model example

* except at extremely low mixing heights

3.3.5 Fit of the Modelling to the Monitoring Results

With the model sensitivities determined in the previous section, the fit of the modelling results to the monitoring results was revisited.

In the earlier Auckland and Wellington examples, ratios of approximately 1.7 for the observed to modelled peak concentrations of carbon monoxide were seen (see sections 3.3.1 and 3.3.2). Taking the Auckland case, the modelled results were multiplied by this 1.7 factor and then compared with the non-scaled modelled results against the observed results (see Figures 3.24 and 3.25) to assess any improvement in the fit.

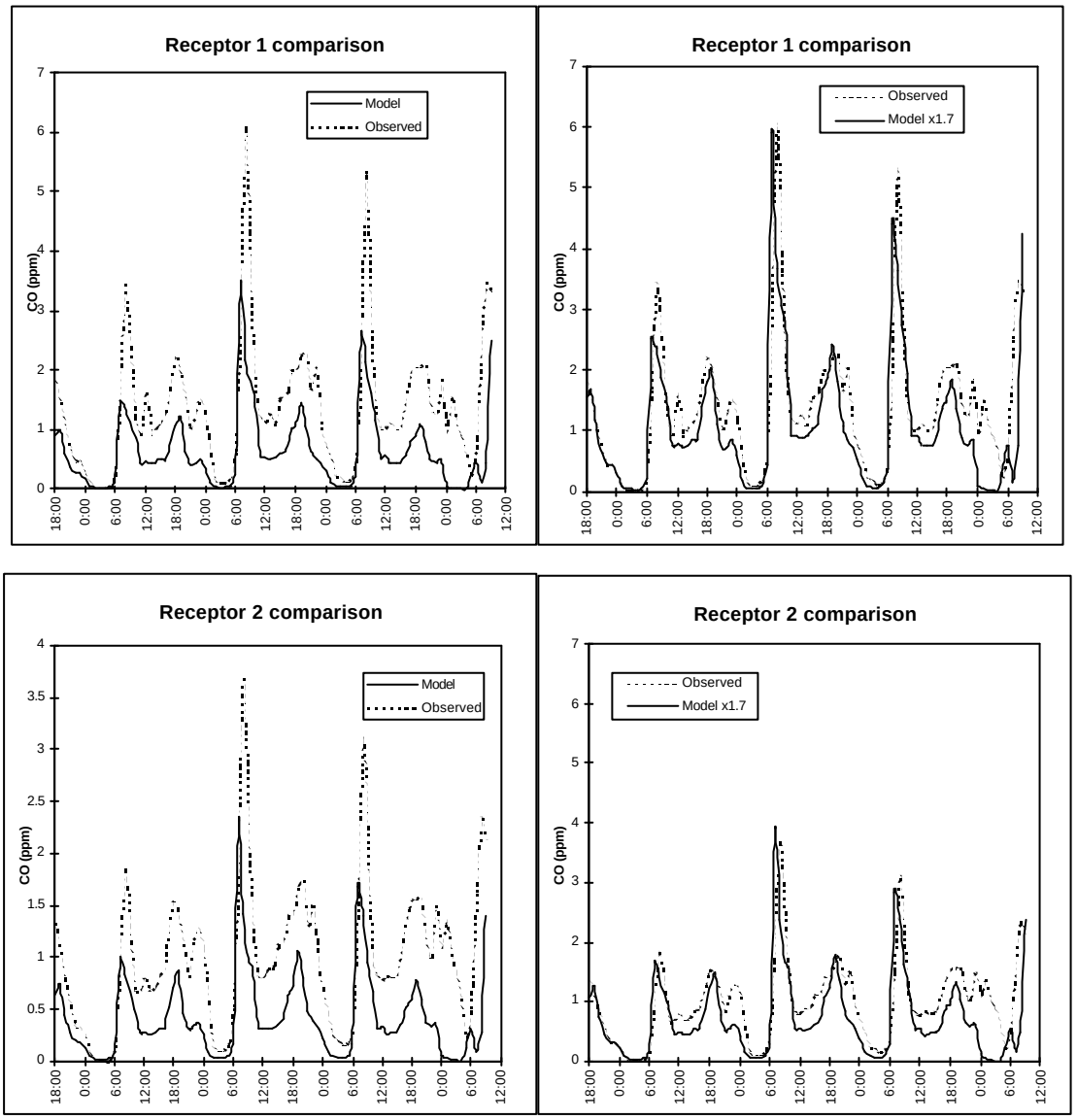

Figure 3.24 Comparison of the modelled to the observed results for the original numbers (left) versus the scaled-up numbers (right) for receptors 1 and 2 in the Auckland case

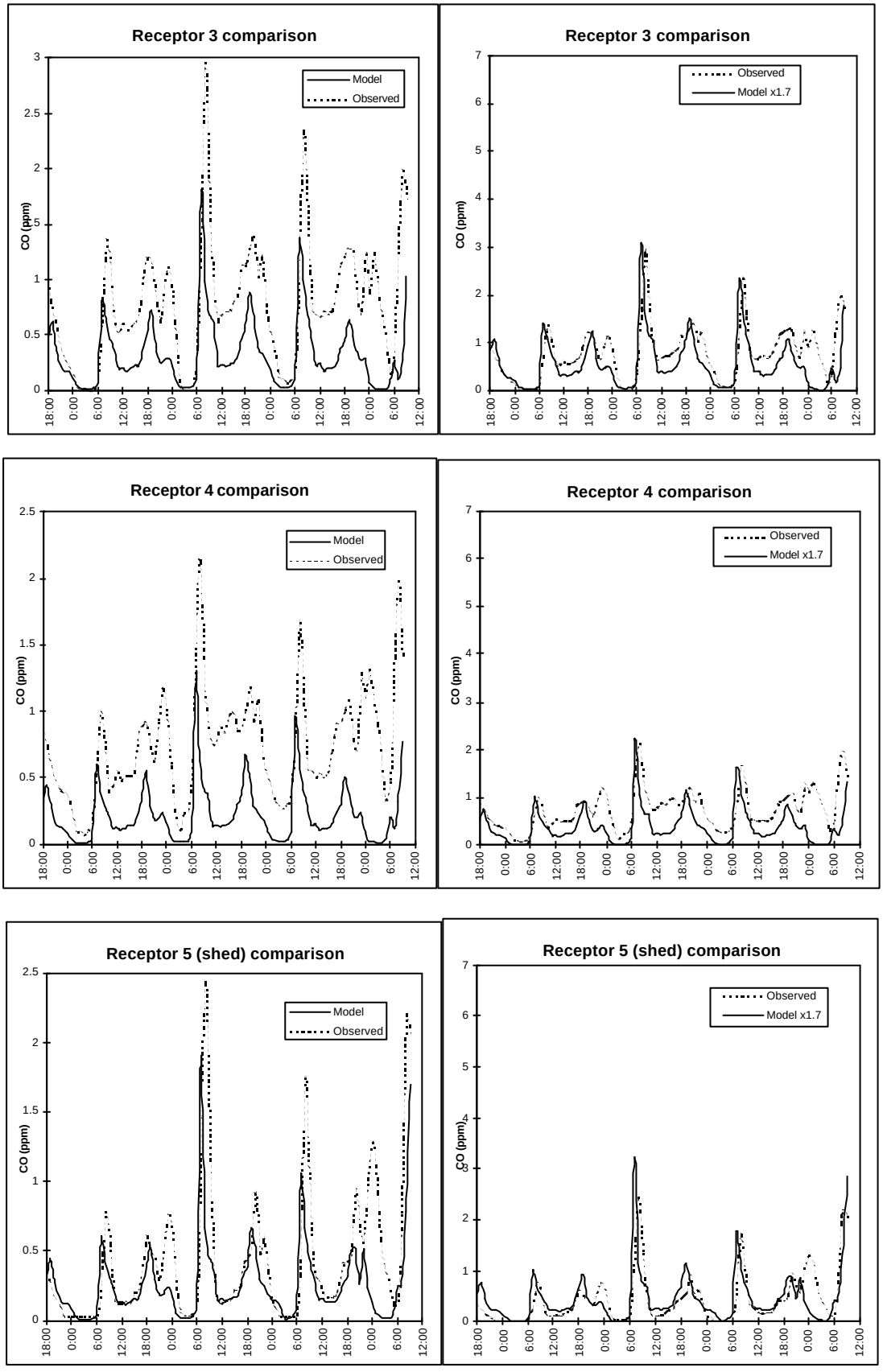

Figure 3.25 Comparison of the modelled to the observed results for the original numbers (left) versus the scaled-up numbers (right) for receptors 3, 4, and 5 in the Auckland case

As can be seen the scaled agreement is extremely good for all receptors suggesting that for the most part the discrepancy in the model fit is more an issue of direct proportionality than some other more complicated relationship. Looking back at the summary table in the previous section (Table 3.10), the likely factors responsible are those related to the source - the traffic count data and the emission factors. The other factors are effectively ruled out as their relationship to concentration would not show up as simple scale factor.

Investigating the source factors further, the model was always expected to differ slightly from the observed as it used the same average traffic count value for every day whereas the actual traffic count varied for different days of the week. Day to day traffic count variations explain the minor differences at times but not, however, the required overall increase by a factor of 1.7. This is more likely caused by an under-estimation in the emission factors.

Although the emission factors used in this work are from up to date (yet to be published) work done for New Zealand specific conditions and are more relevant than any others used in previous studies, their applicability to this project still relies on several key assumptions as follows:

- the emission factors represent the **average emission rates** for specific drive cycles which are composites of individual events (e.g. several accelerations, a period of steady state, a deceleration etc. etc.)

  As the monitoring is at a single location and at a single instant, it is more likely to be influenced by specific individual events which may have significantly higher emission rates than the average for the total driving cycle.

  *Further work has been planned to investigate the effect of distance **along** the roadway on the concentration monitored to establish typical ranges of dependency.*

- cold-running was factored in to the travel of **light duty petrol vehicles only** in the fleet as other cold-running emission factors were not available

  Although light duty petrol vehicles represent the greatest fraction of the overall vehicle fleet, comparable increases in the emissions for other vehicles affected by cold-running would still increase the overall source emissions.

- the influence of cold-running was estimated for all three sites based on the **"all or nothing"** assumption that it only affects the first three minutes of driving and thereafter is not significant

  The effect of cold-running is more likely to follow a gradual dropping off from cold start which extends past the three minute cut-off to have some influence (albeit reduced) beyond this point resulting in higher emissions for vehicles taking longer than three minutes to reach the roadway.

- the proportion of cold-running vehicles at each site was **an estimate** for each site based on the proportion of vehicles most likely taking three minutes or less to reach the roadway considering the location of residential areas and the average trip length

Cold-running was only factored into emissions for the Christchurch site and even then only for 20% of the vehicles. It is possible that the actual influence was greater for all three locations but further work is needed to verify this.

Just to illustrate the point about the influence of cold-running, consider the Auckland example as follows:

The original fleet emission factor for congested flow, assuming no cold-running was

=> 17.12 g/km (from Table 3.4)

Increasing this by 1.7 would give a new scaled fleet emission factor of

=> 29.10 g/km (1.7 * 17.12 g/km)

Removing the contribution of the other vehicles at 1.08 g/km, the whole light duty petrol fraction would need to contribute

=> 28.02 g/km (29.10 - 1.08 g/km)

As the light duty petrol vehicles represent 79.8% of the fleet, the light duty petrol emission factor would be

=> 35.11 g/km (28.02 / 0.798 g/km)

If we let X be the proportion of cold-running affecting the light duty petrol vehicles then

=> $X * 57.70 + (1 - X) * 19.90 = 35.11$ g/km

where

57.70 is the cold-running emission factor
19.90 is the normal congested flow emission factor

Rearranging and solving gives

=> $X = 0.402$ ((35.11 - 19.90) / (57.70 - 19.90))

Consequently an increase of 1.7 in the source emissions could be achieved by increasing the proportion of cold-running in Auckland to 40% which is not outside the realm of possibility.

3.4 Other Contaminants

Although the original brief included other contaminants, this study has focussed strongly on carbon monoxide. After the work was underway, it became clear that far more was to be gained by concentrating on the carbon monoxide measurements for several reasons (of which all have been validated by the excellent results obtained):

- CO has been shown to be more of a problem, with regular guideline exceedences near roadways (whereas other contaminants have not yet been shown to have as many exceedences).
- CO is a better tracer of emissions, because of its relative stability in air.
- CO is easier to measure reliably.
- CO is well-correlated with particulate emissions (but not necessarily with other contaminants).
- CO is easier to model for transport effects, since there are fewer other sources in many locations.
- More detailed, and useful, results have been obtained by putting more effort into the CO analysis and modelling.

Despite the focus on CO, it has been possible to make reasonable inferences about two of the other principal transport-related contaminants - PM_{10} and NOx - based on monitoring that has taken place in this study combined with previous work (*Nichol et al 1997*).

3.4.1 Fine Particulates (PM_{10})

High particulate levels are experienced in some urban locations, mainly in winter when the major contributing factor is emissions from domestic heating using wood and coal burning. This is particularly so in Christchurch, where very high concentrations can occur during cool, calm, winter nights. However in some locations, where domestic burning is minimal, the major contribution comes from vehicle emissions. This is the case at the North Shore site in Auckland, where there is a very well-defined relationship between CO and PM_{10} concentrations.

From preliminary work conducted, using several months of measurements at the St Albans site in Christchurch, and the North Shore site in Auckland, the following relationships have been developed:

St Albans - Christchurch

PM_{10} (in $\mu g/m^3$) = CO (in mg/m^3) x 20 ($\pm$ 12 $\mu g/m^3$)

North Shore - Auckland

PM_{10} (in $\mu g/m^3$) = CO (in mg/m^3) x 8 ($\pm$ 2 $\mu g/m^3$)

For example, in Auckland, near the northern motorway, if CO is measured at 10 mg/m^3, then the PM_{10} concentration will be 80 µg/m^3 (± 2 µg/m^3).
The higher variability (± 20 µg/m^3) in the Christchurch relationship is due to the complication of other sources (particularly solid fuel heating in winter), but it is expected that in summer the correlation would be as good as in Auckland.

PM_{10} measurements were made during this current study using a TEOM in Auckland and MiniVol samplers in Wellington and Christchurch (see *Appendix* V). These confirmed a definite correlation between CO and PM_{10} consistent with the above analysis.

Although the ratio of CO to PM_{10} emissions for any particular vehicle or transport scenario will vary, it is generally acceptable to infer that any management strategy developed to reduce emissions of CO to meet air quality guidelines will likely have the same effect for emissions of fine particulates (excepting major technology changes).

3.4.2 Nitrogen Oxides (NOx)

Oxides of nitrogen (NOx) comprise nitrogen oxide (NO), nitrogen dioxide (NO_2), and trace amounts of other oxides. The ratio varies over time, as NO is oxidised to NO_2, and can vary from almost all NO near the source, to almost all NO_2 after 12 to 24 hours.

Although NOx is commonly used as an air quality indicator, it is not a good indicator of health or nuisance effects. NO_2 has several detrimental effects, but NO generally does not. Thus NO_2 should be used, since a high concentration of NOx can be anything from highly damaging (if it is mostly NO_2), to essentially innocuous (if it is mostly NO).

Previous work has shown that NO_2 is very poorly correlated with CO, and by inference, with traffic. Measurements made in Dominion Rd., Auckland during 1994/95 show this effect (*Nichol et al 1997*) where there is almost no correlation between high concentrations of NO_2 and high concentrations of CO. The major reason for this is that most of the NOx emitted directly from motor vehicles is NO. NO_2 is emitted as a primary pollutant in small quantities but the majority present in the environment is secondary NO_2 which results from the oxidation of the NO over time. Consequently, high concentrations of NO_2 can often be due to events that occurred at some distance away, and several hours previously.

Specific NO_2 measurements were not made during the current study because of the reasons outlined above and also because of problems in getting appropriate equipment. It is relatively difficult and expensive to make measurements which are accurate and reliable enough.

Again as for PM_{10}, it is generally acceptable to infer that any management strategy developed to reduce emissions of CO to meet air quality guidelines will likely have a similar effect for emissions of nitrogen oxides (excepting major technology changes).

3.4.3 Other Pollutants

Transport activities are also the source of a wide range of other pollutants. The main ones of potential concern are various hydrocarbons from evaporation and combustion of fuels, such as benzene, toluene, and formaldehyde.

No attempt has been made to deal with these pollutants in this study because, in addition to being extremely difficult and costly to measure, hydrocarbons do not have much data readily available on emission factors.

However, preliminary monitoring data from another study underway has shown that it may be possible to study and model some hydrocarbons by examining their ratio to other pollutants. For instance, it appears that there may be a good correlation between benzene and CO concentrations from measurements taken at an inner city location. If these relationships can be validated and generalised, then a more detailed picture of transport effects can be established with modest, carefully-designed studies.

4. Summary and Conclusions

This study was commissioned by the Ministry of Transport and the Ministry for the Environment to investigate the nature and impacts on air quality of emissions from motor vehicles in New Zealand to establish:

- what are key factors affecting roadside pollution levels ?
- how can we accurately predict pollutant concentrations near roadways ?

to provide technical input for formulating future policy and management options in the transport sector.

Monitoring and modelling work was undertaken at three sites, which were selected as being representative of typical New Zealand roadways. This section summarises the key activities, and findings arising from the study with some discussion on the implications for the future and how the model can be applied in other locations in New Zealand.

4.1 Key Activities

4.1.1 Determination of Source Characteristics

All data related to source characteristics were determined to be consistent with other work being undertaken by the Ministry of Transport as part of the Light Vehicle Fleet Strategy and the Ministry for the Environment as part of the Sustainable Management Fund Vehicle Emissions Testing Program.

Road Types

The three sites selected covered the following road types:

Site	Road Type	Terrain
North Shore, Auckland	*motorway*	flat
Ngauranga Gorge, Wellington	*motorway*	hilly
Riccarton Road, Christchurch	*central urban*	flat

Vehicle Fleet Mix

The vehicle fleet mix was taken from vehicle registration data for 1996 and broken down into seven vehicle categories covering various vehicle duties, different fuel types, and motorcycles. Although figures were available for each site, the differences between the locations were insignificant so a single national fleet mix was chosen to be representative for all sites in New Zealand. Light duty petrol vehicles were found to dominate the fleet, contributing around 80% of all vehicle kilometers travelled (VKT).

Emission Factors

General emission factors for the light duty petrol vehicles were developed for four different traffic flow regimes - cold-running, congested, interrupted, and freeflow - from actual vehicle exhaust measurements undertaken by Auckland UniServices. The results showed significantly higher emissions of carbon monoxide arising from actual New Zealand driving cycles than from overseas test driving cycles. Emission factors for the remainder of the fleet were developed from a survey of the relevant literature and checked against the latest New Zealand factors for relativity.

From a detailed investigation of the traffic patterns at each site, the traffic numbers and traffic flow regimes were found to vary significantly with time of day requiring different factors to be used at different times of the day also. These specific emission factors were determined assuming the worst case traffic flow regimes.

4.1.2 Monitoring

Field work took place at the three sites between 21 January and 14 June 1997 as follows:

North Shore - Auckland

Monitoring was conducted for five periods between 21 January and 21 March 1997 at Westlake Girls' High School bordering State Highway 1.

Measurements of carbon monoxide (CO) were taken using five electrochemical sensors and a continuous analyser located at distances from 3.2m up to 73.2m from the roadway.

Wind speed and wind direction were measured at a height of 10m using meteorological equipment already located at the site.

A TEOM analyser, also already located at the site, was used to measure fine particulates (PM_{10}) and provided continuous concentrations.

Ngauranga Gorge - Wellington

Monitoring was conducted for three periods between 29 April and 14 June 1997 at a Wellington City Council pumping station adjacent to State Highway 1 in the Ngauranga Gorge.

Measurements of carbon monoxide (CO) were taken using three electrochemical sensors and a continuous analyser located at distances from 8.6m to 31.7m from the roadway.

Wind speed and wind direction were measured at a height of 3.4m using a portable mini-meteorological station.

A portable MiniVol sampler, was used to measure fine particulates (PM_{10}) and provided average concentrations covering several days.

Riccarton Road - Christchurch

Monitoring was conducted for four periods between 8 May and 9 June 1997 at the railway crossing at the Hagley Park end of Riccarton Road.

Measurements of carbon monoxide(CO) were taken using five electrochemical sensors and a continuous analyser located at distances from 7m to 120m from the roadway.

Wind speed and wind direction were measured at a height of 1.8m using a portable mini-meteorological station.

A portable MiniVol sampler, was used to measure fine particulates (PM_{10}) and provided average concentrations covering several days.

4.1.3 Modelling

The USEPA approved model, CAL3QHC, was chosen for the modelling of carbon monoxide concentrations. This model is normally only applied in situations where the wind speed is greater than 1 m/s and therefore needed to be modified to handle the calm conditions which frequently occur in many New Zealand locations and are often associated with high pollution events.

The development of the model progressed through the following stages:

1. Initially, CAL3QHC was applied to the North Shore - Auckland monitoring data to achieve as good a fit as possible for normal to high winds.
2. CAL3QHC was then applied to the Ngauranga Gorge - Wellington monitoring data to derive default inputs suitable for calm conditions and consistent with the fit achieved for Auckland.
3. Finally, the modified modelling system was tested on Riccarton Road - Christchurch data to validate the process.

4.2 Key Findings

4.2.1 Factors Affecting Roadside Pollution Levels

Absolute Concentration at the Roadside

From the monitoring results, a range of factors were found to affect the roadside pollution levels as follows:

Factor Type	**Variable**
source strength	• vehicle numbers • emission factors*
wind data	• wind speed • wind direction
atmospheric stability	• stability class • mixing height
site characteristics	• terrain • traffic configuration • proximity of buildings

* emission factors are a function of vehicle speed and road type

For example, the daily pattern in carbon monoxide mirrored traffic flow rates which exhibited sharp peaks for morning rush hour traffic and broader peaks during the afternoon / evening at

both North Shore and Ngauranga Gorge. Although the pattern at Riccarton Road was slightly different, with traffic remaining at constant high levels from the early morning until late evening, this was again reflected in the monitoring results.

In addition, the observed concentrations also reflected the changes in wind speed and atmospheric stability as concentrations tended to increase for periods with low wind speeds but suddenly decreased as the wind speed increased (assuming the wind direction remained constant).

Concentration Change vs Distance

Generally, carbon monoxide concentration was found to decrease with distance but this occurred in a highly variable way. Some situations recorded a sharp drop in concentration whilst others produced a near plateau.

From model runs using CAL3QHC, the effects of these factors were able to be quantified and prioritised. The most important factors were found to be:

Input Parameter	Effect
Vehicle Numbers *Emission Factors*	proportional
Wind Direction *Wind Speed* *Stability*	complex relationships

4.2.2 Predicting Pollutant Concentrations Near Roadways

Modelling of CO

Comparing modelled results with observed results at all sites, CAL3QHC was found to reproduce all trends extremely well - particularly the sharp morning peaks and flatter afternoon peaks typical of diurnal traffic patterns. There was, however, some under-prediction in the absolute values, with the observed results being approximately 1.7 times the modelled results.

When the modelled results were scaled up by 1.7 and compared again to the observed results, the agreement was almost perfect for all receptors, suggesting that for the most part the discrepancy in the model fit was more an issue of direct proportionality rather than some other more complicated relationship. From an investigation of the relationship between modelled concentration and the different factors (see table above), the variables most likely to be responsible are the emission factors.

Although the emission factors used in this work are the most comprehensive and relevant to date, their applicability to this project still relies on a number of key assumptions which on closer examination indicate that higher numbers could well be justified in the situations modelled for two major reasons. Firstly, the emission factors represent average factors developed for specific drive cycles which are composites of many individual events, some of which may have significantly higher emission rates. A future project is planned to establish the typical ranges of emissions versus distance along the roadway. Secondly, cold-running was assumed to affect only

the first three minutes of driving and thereafter was not considered significant. The proportion of vehicles affected was estimated based on the proximity of residential areas to the roadway being studied. It is quite possible that both the effect and proportion of cold-running were higher but further work needs to be done to verify this.

On balance, the evidence suggests that using the scaled version of CAL3QHC is appropriate and will provide reasonable and accurate predictions of CO concentrations.

Modelling Other Pollutants

Although the original brief included other contaminants, this study has focussed strongly on carbon monoxide. However, results of monitoring undertaken in this study combined with other work has enabled some inferences to be made about other transport-related pollutants.

Fine particulates (PM_{10}) appear to correlate well with CO results in a linear relationship of the type $PM_{10} = a * CO$. Correlations have been developed for two sites - North Shore (Auckland) and St Albans (Christchurch) - but more work needs to be done as the multiplication factor(a) varies from site to site and probably season to season (due to influences of other sources).

Oxides of nitrogen (NOx) are more difficult to relate to CO as they represent a family of compounds including nitric oxide (NO), nitrogen dioxide (NO_2) and others. Although NO is more easily related to CO, it is relatively innocuous in terms of health effects when compared to NO_2. Unfortunately, there is almost no correlation between high concentrations of NO_2 and high concentrations of CO because the majority of NO_2 present is produced from oxidation of NO over time.

Hydrocarbons have not been addressed in this study but preliminary results from another study underway have shown that there may be good correlations between some compounds (such as benzene) and CO but these relationships need to be developed further.

4.3 Key Implications

4.3.1 Future Application to Other Roadways

Overall Comments

CAL3QHC has been developed in this work to handle a wide range of meteorological conditions (including calm conditions) and has been shown to match the observed results very well, provided that care is taken over the model input parameters.

Generally, actual observations made at the time the model is being applied to are far preferable to using default input settings. This has, as far as is possible, been applied to the modelling of field work data, when meteorology and carbon monoxide measurements were made simultaneously. Stability classes were derived for the sunshine amount and wind speed. Only traffic count data were averages over a 5-day period (Monday to Friday) - individual days varied only slightly. Considering likely errors in the emission factor assumptions, future applications of the model should utilise the scaled version to increase model predictions by a factor of 1.7 to give more realistic carbon monoxide concentrations.

Applications to Other Roadways

The modified CAL3QHC model can now be applied to other similar roadway cases where there are no CO monitoring data available in order to produce reliable predictions of CO concentrations. Various default modes can be used, depending on the level of information available for the site, but the more actual data available the more accurate the prediction will be. If meteorological data are unavailable the model is applied in "screening mode" where realistic defaults must be employed to produce conservative estimates.

The following gives guidance on the default input parameters to select (see *Appendix VI* for the format of the input data file for CAL3QHC). Allowable limits are square-bracketted.

- *Meteorological Variables:*
  - wind speed equal to 1*m/s* [1, ∞].
  - all wind directions from 0° to 360° in intervals of 15°
  - stability class B for day-time, F for night-time, D for sunrise/sunset. For hazy mornings, still use F up to peak traffic time [A, F].
  - mixing height equal to 1000*m* (the model is insensitive to this)
- *Dispersion Parameters:*
  - averaging time 60 *min* [30,60]
  - surface roughness 5*cm* (the model is not sensitive) [3*cm*, 400*cm*]
  - settling velocity and deposition velocity both zero for carbon monoxide.
  - ambient background concentration zero for carbon monoxide (assuming contribution from motor vehicles only)
- *Site Parameters (link data, geometry):*
  - number of links can be 1 (as it is the nearest road link that is most important)
  - roadway link co-ordinates, including height [-10*m*,10*m*] must be specified. Length [10*m*, 10000*m*] must be greater than width.
  - link type; "at grade","fill","bridge", or "depressed"
  - link width [10*m*, ∞]. equals road width plus a 6*m* mixing zone
  - receptors at distances 10, 20, 30, …, 100*m*, outside the mixing zone at a height of 1.8*m*
- *Traffic Variables (for each link):*
  - traffic volume peak time maximum 1400*veh* hr^{-1} on urban roads, 3500 *veh* hr^{-1} on motorway (as good an estimate as possible is preferable)
  - composite running emission factor given by source determination calculations (convert to *g* veh^{-1} $mile^{-1}$). Use the "congested" value for worst case.

Traffic Queues at Road Intersections

Emissions, and consequently concentrations of carbon monoxide are likely to be larger for idling vehicles in traffic queues than from free flowing traffic. CAL3QHC can deal with, and has elsewhere been successfully applied to, traffic light-controlled junctions. Given information on the signal phasing, the model calculates the average queue length, and given idling emission factors will calculate the resulting carbon monoxide concentration. This issue has not been addressed in the present programme but would be a natural progression from the work undertaken here.

4.3.2 Application to the Traffic Corridor Concept

In order to assess the effects of vehicle emissions on local air quality, the concept of a "traffic corridor" can be considered. Typically, air quality impacts are assessed in terms of either direct effects from an identified point source (such as a power station stack), or in terms of the overall effect of a wide variety of general emissions on an air shed. Either of these approaches can be appropriate for transport emissions - by using the roadways as line sources - but they are do not focus on one of the crucial issues which is "what is the worst effect of transport emissions?"

As shown in this study, peak concentrations of contaminants occur relatively close to major roads and in many circumstances disperse quickly. Thus the concept of a traffic corridor, defined as a particular zone of effect is a useful tool for assessing the traffic-related effects in relation to effects from other sources.

The concept is relatively simple, and easy to understand. It is postulated that there is a defined zone around any road or intersection within which the effects of emissions from that road dominate. For small rural roads, the zone might be negligibly small having no significant effect on anyone. For moderately busy urban roads, it might be a few meters wide only affecting road users and pedestrians. For very busy central business district roads, it might be tens of metres wide possibly affecting businesses and residences near the road.

However, it is very difficult to define this traffic corridor, since it depends on several factors. These include:

Sources	how many vehicles?, what type?, what sort of traffic patterns?
Weather	wind speed, wind direction, stability and turbulence levels
Site Features	buildings, hills, intersections

Using the modified CAL3QHC model developed in this study, it will now be possible to define a maximum envelope of influence, and use this to define the traffic corridor for any given roadside location. Adequate meteorological data is available for most locations, and the site conditions can be reasonably well-specified in most cases. The most difficult quantity to estimate is the traffic emissions. Even if the vehicle numbers are well known, their emissions characteristics are not obvious, as demonstrated in this study. However with improved measurements currently being undertaken, and extending the results of this study, it will be possible to make reasonable estimates.

Once the traffic corridors have been defined, it will be possible to assess the extent of community exposure to direct transport emissions, and to monitor these for trends in testing the efficacy of new policy and management options.

4.4 Summary of the Model Capabilities

This study has demonstrated very clearly that the effects of carbon monoxide emissions from transport can be modelled with a high degree of accuracy in many circumstances. By considering the relevant factors carefully, it is possible to model the effects of other contaminants as well. It is also possible to model any given scenario or roadside location if enough information is available.

Model Input Requirements

A very good description of the effects can be obtained if the following information is acquired:

Meteorology

This is the most important variable. The model requires accurate hourly values of wind speed, wind direction, and atmospheric stability. Other parameters such as the temperature and mixing height are required but estimates of these are adequate and can usually be obtained for most locations.

Emissions

Some estimate has to be made of the roadway emissions of whatever parameter is being examined. This requires data on the road type (e.g. motorway, central urban), traffic flow regime (e.g. cold-running, congested, freeflow) and traffic volumes on an hourly basis. Then some estimate has to be made of the vehicle fleet composition (e.g. light duty petrol, heavy duty diesel) so that the appropriate emissions factors can be applied to get the source strength.

Site Geometry

The geometry of the site needs to be considered such as the number and orientation of roads, the presence of hills, the effects of buildings, and the type of ground surface around the site. These are all still fairly subjective. For instance, there are no hard rules on how far away from the site roads should be included. The Auckland situation suggests 50-100m, but the Christchurch case showed that greater distances may need to be considered. Furthermore, the model currently does not handle steep terrain nor dense building layouts, so that in situations where these occur the results may be skewed. Finally, some information is needed on the deposition rate (or loss rate) of the contaminant, particularly to the surface. This is highly variable, and depends on a number of factors, such as vegetation, ground cover, rain, temperature and the type of contaminant. At present these loss rates are estimated.

Existing Background Concentrations

Some assessment needs to be made of the existing background concentration of the contaminant of interest. In many cases this will be low or negligible - such as CO from a major isolated road. However in some cases the existing concentrations may be high - such as particulates in a wood burning area, or for roads in major industrial or urban centres. In ideal circumstances, some monitoring information should be obtained.

Ease of Use

Once the basic meteorology and emissions data are available, the model can be run to produce estimates of effects on either a case-by-case basis, or over longer terms. The model itself is available freely from the USEPA Public Bulletin Board, but is relatively complex to run. It is not as user-friendly as many dispersion models and involves several linked modules so it is highly recommended that this task be performed by someone experienced in dispersion modelling.

Exposure Assessments

After the model is set-up and producing sensible outputs, it can also be used to make an assessment of community or ecosytem exposure to the contaminant of interest. This can be done simply by plotting the ground level concentrations and overlaying these with population or ecosystem sensitivity maps. Developing a methodology for this, and trialling it with a preliminary assessment of exposure to CO is one of the next steps in the research programme.

Application to Other Contaminants

Finally, the model works well with carbon monoxide, and probably with other simple contaminants which are predominantly emitted by transport, such as benzene. It will not work as well with contaminants which transform in the atmosphere or have wider scale effects, such as nitrogen dioxide, unless a much wider network of roads is taken into account. This is because the nitrogen dioxide affecting a particular site may have come from nitric oxide emitted from vehicles (or other sources) several kilometres away. Caution is also needed when modelling parameters which may have significant background concentrations, which must be added to the model results to gain a true assessment of effects.

In summary, the modelling system is available for wider application throughout NZ, and can be used in many circumstances to make good assessments of effects of emissions from transport. A future step is to develop and apply models of greater scope, which can cover entire airsheds and be linked to the model used here to give a complete picture of the effects of transport emissions over whole cities.

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