A Methodology for the Assessment of Air Quality in London and Bangkok

Auemphorn Mutchimwong

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Abstract

Road transport has a major effect on the air quality in London and Bangkok. As an aid to decision making to control and manage air pollution, air quality models are useful tools and are now applied worldwide. This research aims to modify and adapt a selected screening line source air quality model used in the UK for application in Bangkok as general tools for air quality assessment. The emphasis is on models as an aid to assess various scenarios involving traffic and emissions management. The research also aims to assess air quality in the future years and to propose scenarios to improve air quality in Bangkok. A screening air quality model, suited to this task, was selected from amongst available alternatives: the CAR, DMRB, LEZ, and GRAM models. The DMRB and GRAM models fitted the requirements of the current research. The GRAM model gave better performance than the DMRB model on the predictions of NO_2 and CO, except for PM_{10} in Bangkok. As the DMRB model requires urban background to be specified whereas GRAM calculates the total concentration including urban background levels, it was decided to select the GRAM model and to adapt it from its current UK orientated formulation to make it applicable to Bangkok. Various parameters were examined to identify the differences between London and Bangkok conditions. Following this a new model for predicting NO_2 and PM_{10} was developed, called the Bangkok GRAM model, whose performance in Bangkok was shown to be better than the UK GRAM model. Future projections were also studied and indicated that the NO_2 and PM_{10} levels in London will decrease in future, but that exceedences will still occur. The introduction of more stringent emissions controls and the early introduction of proposed vehicle emissions standards are the additional measures expected to reduce UK urban emissions by up to 30%. Under the current policy on emission reduction in Bangkok the model predicted little decline in NO_2 and PM_{10} concentrations at very busy roadside sites for up to 2010, and continual increase in the future. Scenarios of additional measures are proposed. The emission reduction approach gives significant reductions in NO_2 and PM_{10} concentrations in Bangkok. The model development has clarified where the main uncertainties lie in urban modelling and emphasises the need to describe re-suspended dust accurately, especially in Bangkok.

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Acronyms and Abbreviations

Chemical substances

C_6H_6	Benzene
CO	Carbon monoxide
CO_2	Carbon dioxide
HC	Hydrcarbon
NH_3	Ammonia
NH_4NO_3	Ammonium nitrate
$(NH4)_2SO_4$	Ammonium sulphate
NMVOC	Non-methane volatile organic carbon
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
O_2	Oxygen
O_3	Ozone
PM	Particulate matter

Acronyms and Abbreviations (Cont.)

PM_{10}	Particle with aerodynamic diameter of 10 micrometer or less
$PM_{2.5}$	Particle with aerodynamic diameter of 2.5 micrometer or less
SO_2	Sulphur dioxide
SO_x	Oxides of sulphur
TSP	Total suspended particulate matter
UV	Ultra violet light
VOC	Volatile Organic Compounds

Institution

AQEG	Air Quality Expert Group
DEFRA	Department for Environmnet, Food and Rural Affairs
DETR	Department of the Environment, Transport and the Regions
DfT	Department for Transport
EU	European Union
OECD	Organization for the Economic Co-Operation and Development
QUARG	Quality of Urban Air Group
TfL	Transport for London
UNEP	United Nations Environment Programme
WHO	World Health Organization

Others

BAM	Beta attenuation monitor
GHV	Gravimetric high volume method
HDV	Heavy duty vehicle
LDV	Light duty vehicle
MC	Motorcycle
YCF	Year Correction Factor

Units

h	Hour
km	kilometre
kt	kilotonne
m	Metre
m^2	Square metre
m^3	Cubic metre
µg	Microgramme
mg	Milligramme
ppb	Part per billion
ppm	Part per million
s	Second
t	Tonne
veh	Vehicle
Y	Year
°C	Degree Celsius

Unit conversion

The unit for concentration used in this research is the mass per unit volume, for instance, $\mu g/m^3$. Thus the data from the model provided in the unit of volume per unit volume (mixing ratios) such as ppb, were converted to the unit of mass per unit volume by the unit conversion as the following:

1 ppb NO_x (NO_2)	=	1.905 $\mu g/m^3$ NO_x (NO_2)
1 ppm CO	=	1.16 mg/m^3 CO
1 ppb C_6H_6	=	3.25 $\mu g/m^3$ C_6H_6
1 $\mu g/m^3$ NO_x (NO_2)	=	0.52 ppb NO_x (NO_2)
1 $\mu g/m^3$ CO	=	0.86 ppm CO
1 $\mu g/m^3$ C_6H_6	=	0.31 ppb C_6H_6

These conversions of the ppb and ppm to $\mu g/m^3$ or mg/m^3 are for air temperature of 20°C and atmospheric pressure of 1013 mb. This conversion also applies to the chapters of this thesis.

Chapter 1

Introduction

1.1 Rationale for the research project

1.1.1 Road transport: a major contributor to air quality problems in London and Bangkok

Air quality in urban areas is a major concern throughout the world. It has received increasing attention in the past decade (Mayer, 1999). This has arisen because nearly half of the world's population lived in urban areas by around the year 2000 (Fenger, 1999). Meanwhile most cities worldwide suffer from serious air quality problems. Amongst those cities are London, in the UK, and Bangkok, in Thailand. Air pollution is caused by different anthropogenic processes, which can be categorised into the following source groups: motor transport, industry, power plants, trade, and domestic fuel (Mayer, 1999). A previous WHO/UNEP study on urban air pollution in twenty megacities (cities with a projected population of over 10 million by the year 2000) of the world, concluded that the main air quality problem at a half of those megacities, including London and Bangkok, was attributable to road transport (WHO/UNEP, 1993). Numerous studies conducted in various cities around the world also confirmed this conclusion (e.g. Faiz, Gautam and Burki, 1995; Chiquetto and Mackett, 1995; Mage et al, 1996; Garza, 1996; Stein and Toselli, 1996; Bogo et al, 2001). In this research London and Bangkok are the cities of interest, but the general conclusions are expected to be applicable elsewhere.

At the present time road transport is regarded as the major source of urban air pollution in London (Mage et al, 1996; DOT, 1996; LRC, 1997; DETR, 1999, 2000a; DEFRA, 2003a). From the evaluation of the first round of air quality reviews and assessments, more than 100 air quality management areas (AQMAs) have been declared in the UK, which represents about one-third of the local authorities in England, Wales and Scotland (Air Quality Consultants Ltd. and University of West of England, 2002). Of these, the vast majority of declarations are related to road traffic emissions, for which the major contributors of harmful pollutants are NO_2 and PM (DEFRA, 2003a; Lim, Hughes, and Hellawell, 2004). Even though, predictions of road transport emissions of these two pollutants showed that they are going down

(AQEG, 2004a, 2004b), it was estimated that under the current emission reduction policies, NO_2 and PM_{10} levels at many roadside sites and some background locations will still be exceeded in London in 2010 (DEFRA, 1999a, 1999b). It was expected that the total transport emission may start to rise if vehicle number increases (AQEG, 2004a, 2004b). Due to the fact that the vehicle numbers will still increase, under the current emission reduction policy, the exceedence of air pollutant objectives seems likely to eventually increase in future years. Recently, there has been discussion in the UK to control transport emissions and a number of additional options were assessed (Mediavilla-Sahagún and ApSimon, 2003).

Road transport has long been recognized as a major contributor to air quality problems in Bangkok (Mage et al, 1996; PCD, 2000b, 2001, 2002, 2003a). Recently, the observed NO_2 and PM_{10} (gravimetric method) concentrations in Bangkok have tended to decline. Nevertheless the annual mean NO_2 at some roadside sites are still above the WHO guideline of 21 ppb, and the annual mean PM_{10} (gravimetric method) at most of the monitoring sites breaches its standard of 50 $\mu g/m^3$ (PCD, 2004a). In recent years, the concern on the O_3 level is growing, because its levels observed at the urban background areas downwind from the centre of Bangkok often breached the 1-hour mean standard of 200 $\mu g/m^3$ (PCD, 2001, 2002, 2003a). This might indicate that Bangkok may be experiencing a photochemical smog problem as well. However, the interest of this thesis is in the NO_2 and PM_{10} levels. The main source of these pollutants is road transport, which is increasing at a rate of around 9% a year in Bangkok (Department of Land Transport, 2004). The concentration, the degree of emission reduction and the effectiveness of options to reduce these two pollutants in Bangkok as well as in London in the future years need to be known, in order to improve air quality to meet the limit values of the respective guidelines or standards. Thus, an appropriate assessment methodology to answer these questions should be carefully designed to fulfill the purpose.

1.1.2 Air quality modelling: a valuable tool for air quality review and assessment

The assessment tools for air quality, as stated in the EU directive (European Community, 2004), are any methods used to measure, calculate, predict or estimate the level of a pollutant in ambient air. Ever since early studies, the level of a pollutant

has been quantified in various ways. These include recording adverse symptoms that result from breathing polluted air, direct measurements of air pollutant levels and the use of automatic monitoring stations and networks. All of these assessment methods, however, give an indication of the past or current state of air pollution but are unable to estimate the quality of air in the future (Fenger, 1999). The advanced instruments. such as the automated air quality monitoring devices, can provide the most up to date data, as real time data readings. However the spatial and temporal coverage of air quality measurements are limited; monitoring data normally are not sufficient as the sole basis for demonstrating the adequacy of emission limits for existing sources (USEPA, 2003). Air quality models, one of the assessment methods, can complement this task. Thus models have become a primary, valuable analytical tool in most air quality assessments for a variety of reasons (DEFRA, 2003a; USEPA, 2003). They can provide temporal and spatial assessment of air quality changes. They are able to provide levels of pollutants at a point downwind of one or more emission sources (Canter et al, 2000) in areas that are not sufficiently covered by measurements, or to investigate current and future air quality scenarios (Lim, Hughes, and Hellawell, 2004), and to determine the effectiveness of emission controls and changes in source emissions (DEFRA, 2003a). However the use of air quality measurements alone could be preferable, when models are found to be unacceptable, and monitoring data with sufficient spatial and temporal coverage are available (USEPA, 2003). In practice for London and Bangkok this is not the case, and air quality modelling was the chosen methodology for air quality assessment in this research.

Today air quality models have been used worldwide. The US air quality models are available to the public via the Internet network, and they are developed as general models which contain the possibility of being applied elsewhere. Hence they have been used in many countries. The examples of air quality models developed in the USA are the CALINE model, CALPUFF model, and the ISC model (USEPA, 2003, 2004). A number of air quality models used worldwide have also been developed in Europe, i.e. the Danish-OSPM model (Berkowicz et al, 1996), the UK-ADMS model (CERC, 2004a), the Swedish-Indic AirViro system (SMHI, 2000), etc. Most of the European air models are not generally available to public. Instead, the applications of the European air models are often undertaken under a co-operative agreement.

The examples of the application of air quality models worldwide are as follows. In Australia, the CALPUFF model, ISC3 model and the AUSPLUME model are specified as the regulatory air quality models for air quality assessment (The University of New South Wales, 2004). The modification of the CALINE4 model for the analysis of aerosols generated by vehicles on roads was applied in the Brisbane area (Gramotnev et al, 2003). In New Zealand, the nearby country to Australia, the dispersion of PM_{10} episode in Christchurch during a winter time was studied by the CALPUFF model (Barna and Gimson, 2002).

The estimation of air pollution loads onto the marble Arch of Titus in Rome by the CALINE3 model (Metallo, et al., 1995) is an example of the usefulness of air quality models applied in Europe. In France, the CALINE3 model, the Danish-OSPM model, and the ADMS model were used in estimating the concentrations of air pollutants in several studies (i.e. Sacre, Chiron, and Flori, 1995; Vardoulakis, Gonzalez-Flesca, and Fisher, 2002; Soulhac et al, 2003). In UK local air quality reviews and assessments, air quality models, such as the DMRB model, the CALINE4 model, the ADMS model, and the Indic AirViro system were used in several local district areas (i.e. Execter City Council, 2000; Mid Beds District Council, 2000; Hertfordshire Council, 2001; Leicester City Council, No date). The impact on health for the population living nearby a Portland cement plant in Catalonia, Spain was estimated by the ISC3-ST model (Schuhmacher, Domingo and Garreta, 2004). The CALPUFF model incorporating a GIS based decision support system was used for estimation, visualization and analysis of air pollution for large Turkish cities (Elbir, 2004). This model predicted the SO_2 concentration and the predicitons were compared with the measurements in the Mexican oil industry (Villasenor, 2003). The prediction of the Danish OSPM model agreed well with the measurements in a street canyon in Copenhagen, Denmark (Berkowicz et al, 1996). Air quality models were also used in several western countries, e.g. Poland (i.e. Irwin, Niedzialek, and Burzynski, 2001), Finland (i.e. Kukkonen et al. 2001a; Kukkonen et al. 2003), Romania (i.e. Ministry of the Environment, Denmark, 2003), Russia (i.e. Genikhovich et al, No date), USA (Moseholm, Silva and Larson, 1996), Ireland (Trinity College Dublin, 2003), Italy (Deserti, et al. 2004), Hungary (Gyovai and Kiss, 2000), Latvia (i.e. CEROI, No date), Lithuania (i.e. Greičiūtė, Vasarevičius and Auguliené, 2002), and Sweden (i.e. Rapaport, 2002).

A number of air quality models were also developed suitable for local conditions in Asian countries, as well as those developed elsewhere. For example, the Indian Institute of Technology developed an Indian Institute of Technology line source model (IITLS model) and tested it against the CALINE3 model (Goyal and Krishna, 1999). In street canyons in Guangzhou, China, the dispersion of vehicular emissions was simulated by the CALINE4 model and three other simple empirical models named the APRAC model, the Guangzhou empirical model (GZT model), and the pararelled wind and infinite line source Gaussian model (PWILG model) (Chan, Hung and Qin, 1995). In general, it was found that numerous air quality models applicable in Asia were developed in USA and Europe. For instance, the level of NO_2 in and around an Oman liquid natural gas plant was estimated by the ISCST model (Abdul-Wahab, 2002). From a report of the Cambridge Environmental Research Consultants, it was stated that a number of government agencies and academic institutions in China, India, and Malaysia, including South Africa, were amongst the users of the ADMS model (CERC, 2004a, 2004b). The application of the ADMS model was also found in Hong Kong (Huang, Fung, and Lau, 2002). Air quality models were also used in Thailand (i.e. Chongvisal and Limpaseni, 1983; Sripraparkorn, 2001; Pummakarnchana, 2002; PCD, 2004e), Hong Kong (Leung and Hertel, 2000), Malta (Cutajar, 2002), and Singapore (Mukherjee and Viswanathan, 2001).

The evidence as shown above indicate that air quality models were accepted and used worldwide as a valuable tool for air quality review and assessment for both regulatory purposes and academic purposes. In this research, the application of air quality models for the quick and inexpensive assessment of air quality for policy making in connection with the improvement of air quality is of interest.

1.1.3 Main types of air quality models: screening and advanced

Generally, air quality models have two levels of sophistication: screening models, advanced models or refined models (Canter et al, 2000) or more detailed models (Highways Agency, 1999). The last definition is used in the UK and is divided further into two subgroups of intermediate and advanced models (DETR, 1998b). For the application of regulatory dispersion models for air quality assessments in USA, the US Environmental Protection Agency (USEPA) recommends the applications of air quality models in three groups. They are (1) screening tools to be used preceding a

refined modelling study. (2) the preferred, or recommended refined models, and (3) the alternative refined air quality models for use on a case-by-case basis for individual regulatory applications (USEPA, 2003, 2004).

(i) The screening air quality models

The main advantage of this type of air quality model is the provision of a preliminary level of assessment, which has been employed to determine whether there was a problem present, which needs a more detailed air quality model in the assessment (Elsom, 1998). The models require simple input data, consider only one source at a time, and tend to be restricted to one type of source. Screening models usually require no meteorological input and therefore could not take account of local conditions. Most screening models take a few minutes to work out a simple scenario. The models are not expensive. Thus, they provide a very useful way of obtaining quickly and cheaply, a preliminary air quality assessment (DETR, 1998b). The examples of this type of air quality model used in the UK are the DMRB model, and the GRAM model, for which more details given in Chapter 3.

(ii) Advanced air quality models

The models could provide the results more accurately than screening models, but only if detailed and accurate meteorological and emission data sets are available. This type of air quality model requires more information than screening models. Their output choices are more versatile. Specific effects such as atmospheric photochemistry, complex terrain, and building effects could be taken into account. They could take an account of varying meteorology, and they might be able to treat more than one type of source (DETR, 1998b).

However, the advanced air quality models are known to be time-consuming, particularly in the data preparation and analysis stages. They need greater expertise, skill, cost and time to perform an air quality assessment. Hence this kind of model is not appropriate to air quality assessment at the preliminary stage. The models need very detailed meteorological inputs, and may require high capacity computers, such as a workstation, or a powerful PC to run (DETR, 1998b). The models are reliant on expert users. The examples of the models are the ADMS model, and the CALINE model as discussed further in Chapter 3.

This research was interested in a quick and cheap air quality assessment tool for the policy maker in both government agencies and non-government organizations, and the model should have a potential to run a number of mitigation options, so the policy maker can find the best solution to deal with the local air pollution problem. From the benefits and drawbacks of both kinds of air quality model as mentioned above, the screening air quality model was of the interest because it serves this requirement more easily than the advanced model. Even though its accuracy may be somewhat poorer than the results obtained from the advanced model, it is considered as a reasonable tool at the first stage of assessment. Due to the significance of road transport on air quality in London and Bangkok, the screening line source air quality model, as a tool for the assessment of air quality, is the main interest of this research.

1.1.4 The role of air quality modelling in air quality review and assessment under the regulatory purpose in the UK and Thailand

Part IV of the Environment Act 1995 requires all UK local authorities to conduct a review and assessment of local air quality regularly (DEFRA, 2000). If air quality objectives are not met, local authorities must declare these areas as Air Quality Management Areas (AQMAs). The methodology for air quality review and assessment recommended to local authorities in the UK are monitoring or measurement methods, and air quality models. On the same basis as the recommendation on the use of air quality models, the recommended methods for the monitoring or measurement methods are simple and inexpensive at the stage of the screening assessment, and based on automated instruments at the detailed assessment stage (DEFRA, 2003a). The use of screening models, in supplementing the monitoring process, is recommended in the first round of air quality review and assessment at stage two (DEFRA, 2000), and at the second round in the updating and screening assessment (DEFRA, 2003b). More details on air quality review and assessment in the UK are in Chapter 2.

Air quality management in Thailand is operated under the Enhancement and Conservation of National Environmental Quality Act, B.E. 2535 (NEQA, 1992). The review and assessment of air quality in Thailand is carried out locally for regulatory purposes after the National Environment Board declares the area as a pollution control area. There are no recommendations or regulations on the use of air quality models

for review and assessment of air quality in Thailand. In practice, the air quality models have been used in Thailand for over three decades and the computer-based air quality models in both types of screening and advanced models, for more than two decades, as detailed in Chapter 2. However, there are regulations on the measurement methods of air pollutants in ambient air (National Environmental Board, 1995; PCD, 2003b). The regulated measurement methods, both standard methods and equivalent methods, are mostly based on automated instruments, which are not appropriate for air quality review and assessment at the screening stage, unlike those in the UK. On the other hand, it means that the simple and inexpensive measurement methods, which are appropriate for air quality review and assessment at preliminary stage, have not been accepted as the regulatory methods in Thailand.

As far as the author is aware, none of screening air quality models in common use in Thailand has been developed for specific local conditions. Thus the development of a screening air quality model in this research would be a part of a substantial step to improve the air quality assessment tools at preliminary stage, and this model will be a quick and useful tool for the policy maker in Thailand. As mentioned earlier this research has a focus on the screening line source models, the outcome of this research was expected to be a useful tool for assessing the impact of road transport on air quality.

1.2 Aims and objectives

This research aims to adapt and modify a methodology for the assessment of air quality in London for applications in Bangkok. The methodology has focused on a screening line source air quality model. In order to accomplish this aim, the following objectives were undertaken:

(1) To select a screening line source air quality model developed or used in the UK, which has the potential to be modified for Bangkok applications.

(2) To study Bangkok conditions and identify factors that require modifiction in the air quality assessment model.

(3) To evaluate a screening line source air quality model for Bangkok.

(4) To use the modified model to assess air quality in Bangkok up to the year 2025.

(5) To propose scenarios for improving air quality in Bangkok.

1.3 Structure of the thesis

This thesis is arranged in eight chapters. Chapter 1 consists of the significance of the research, the aim and objectives, and the structure of the thesis. Chapter 2 describes an air quality review and assessment in the UK and Thailand. Chapter 3 presents the dispersion models, the application of urban air quality models in the UK, the use of screening models in an air quality review and assessment in the UK, the selection of the models developed or used in the UK, which have the possibility to be modified for application in Bangkok, the evaluation of model performance, and the possibility of altering the model to fit the conditions in Bangkok. Chapter 4 explores the GRAM model, the model selected for modifying to a new model for Bangkok. In this chapter the main concepts, the structure, the formulae, and the model characteristics of the model's sensitivity to the predictions of the road contribution is also included.

In Chapter 5 Bangkok conditions relevant to the model's calculation were studied. The study covers the traffic data, the meteorological data, the NO_x/NO_2 relationship, the emission density, the resuspended dust, the regional background PM_{10}, and the 'Year Correction Factor (YCF)'. In Chapter 6, the development of the new model, named as the Bangkok GRAM model, is described. The performance in the year 2003 is evaluated, and the model sensitivity is studied. The assessment of air quality in London in future years and some scenarios to improve air quality in this city are discussed in Chapter 7. In this chapter, the assessment of air quality in Bangkok towards 2025 is made and some scenarios to improve air quality in this city are proposed. The last chapter, Chapter 8 contains the conclusions and recommendations for future research.

Chapter 2

Air Quality Review and Assessment in the UK and Thailand

2.1 Introduction

This chapter briefly describes the methdoloies for conducting air quality review and assessment in the UK and Thailand. The chapter decribes the process of air quality review and assessment, air quality standards and objectives, monitoring of air quality, and air quality modelling.

2.2 Air quality assessment methodologies in the United Kingdom

2.2.1 Air quality review and assessment

A review of air quality means consideration of the levels of pollutants in the air for which objectives are prescribed in regulations, and estimates of likely future air quality levels. An assessment of air quality is the consideration of whether estimated levels for the relevant future period are likely to exceed the levels set in objectives (DEFRA, 2003b). A review and assessment of air quality is the first step in the local air quality management process. Part IV of the Environment Act 1995 requires each local authority to carry out their review and assessment of local air quality from time to time (DEFRA, 2000). So far, two rounds of the process have been conducted.

At the first round, the review was set out in three progressive stages. Stage One was basically an initial screening of specific pollutants to determine which could fail national target levels. If this showed that one or more locations may have a potential air pollution problem, Stage Two has to be carried out involving more detailed monitoring and modelling for those pollutants and localities where exceedences of the targets were anticipated. Where Stage Two confirmed the likelihood of exceedences, a Stage Three review and assessment was required involving a detailed and accurate study of the specific pollutant(s) including monitoring, modelling and emission inventories. This approach requires the local authority to assess whether the air quality in its areas will meet the objectives and, if not, declare those areas where the objectives will not be met as Air Quality Management Area (AQMAs). If these are declared, local action will then be required to try and ensure compliance with the objectives. From the evaluation of the first round process completed in 2002 (Air

Quality Consultants Ltd. and University of West of England, 2002), over 100 local authorities had designated AQMAs in their areas (DEFRA, 2003b). Most AQMAs are declared in respect of emissions from road transport with only a small percentage from industrial sources alone. The second round process was expected to be completed within 2004. The process is carried out in two steps (DEFRA, 2003b). The first step, an Updating and Screening Assessment for identifying those aspects that have changed since the first round process, includes the conclusion whether the local authority should proceed to a Detailed Assessment or not. This depends on using a checklist to identify significant changes that require further consideration. Where such changes are identified, then the authority should apply simple screening tools to decide whether there is sufficient risk of an exceedence of an objective to justify a Detailed Assessment. A second step involves a Detailed Assessment of those pollutants and the specific locations that have been identified as requiring further work. Quality-assured monitoring and validated modelling methods are suggested in this step to determine current and future pollutant concentrations in areas where there is a significant risk of exceeding an air quality objective.

2.2.2 Air quality standards and objectives

In air quality assessment process, the degree of impacts is determined by the regulated standards or recommended guideline. Presently, air quality standards and objectives for the purpose of Local Air Quality Management in England were set in the Air Quality Regulations (England) (Wales) 2000 and in Air Quality (England) (Wales) (Amendment) Regulations 2002 under the Environment Act 1995. The standards and objectives cover seven pollutants of benzene, 1, 3 butadiene, CO, lead, NO_2, PM_{10} and SO_2. Ozone is not included in the regulations for the purpose of Local Air Quality Management, due to its trans-boundary nature, but ozone continues to be a national objective (DETR, 2000a). The objectives, and target dates are shown in Table 2.1. In addition, the European Union's Air Quality Framework and Daughter Directives prescribe limit values for certain pollutants which all member states, including the UK, must meet its objectives under these Directives as shown in Table 2.1 (DEFRA, 2003b). The EU directive also set the limit value and target date for O_3. Comparing the England and Wales objectives and the EU objectives, the former is set an earlier date to be achieved for all standards.

Table 2.1 England air quality objectives and EU Air Quality Framework and Daughter Directives

Pollutant	England and Wales Air quality objectives			EU Air quality framework and Daughter directives		
	Measured as	Concentration	Date to be achieved by	Measured as	Concentration	Date to be achieved by
Benzene	Running annual mean	16.25 $\mu g/m^3$	31/12/ 2003	-	-	-
	Annual mean	5 $\mu g/m^3$	31/12/ 2010	Annual mean	5 $\mu g/m^3$	20010 [(b)]
1,3 Butadiene	Running annual mean	2.25 $\mu g/m^3$	31/12/ 2003	-	-	-
CO	Maximum daily running 8-hour mean	10 mg/m^3	31/12/ 2003	Maximum daily running 8-hour mean	10 mg/m^3	2005 [(b)]
Lead	Annual mean	0.5 $\mu g/m^3$	31/12/ 2004	Annual mean	0.5 $\mu g/m^3$	2005 [(a)]
	Annual mean	0.25 $\mu g/m^3$	31/12/ 2008	-	-	-
NO_2	1 hour mean	200 $\mu g/m^3$ not to be exceeded more than 18 times a year	31/12/ 2005	1 hour mean	200 $\mu g/m^3$ not to be exceeded more than 18 times a year	2010 [(a)]
	Annual mean	40 $\mu g/m^3$	31/12/ 2005	Annual mean	40 $\mu g/m^3$	2010 [(a)]
O_3	Maximum daily running 8-hour mean[(c)]	100 $\mu g/m^3$ not to be exceeded more than 10 times a year[(c)]	31/12/ 2005[(c)]	8-hour mean[(d)]	120 $\mu g/m^3$ not to be exceeded more than 25 times a year averaged over 3 years[(d)]	2010 [(d)]

PM_{10} (gravimetric)	24-hour mean	50 $\mu g/m^3$ not to be exceeded more than 35 times a year	31/12/ 2004	24-hour mean	50 $\mu g/m^3$ not to be exceeded more than 35 times a year	2005 [(a)]
					50 $\mu g/m^3$ not to be exceeded more than 7 times a year*	2010 [(a)]
	Annual mean	40 $\mu g/m^3$	31/12/2004	Annual mean	40 $\mu g/m^3$	2005 [(a)]
					20 $\mu g/m^3$*	2010 [(a)]
SO_2	15-minute mean	266 $\mu g/m^3$ not to be exceeded more than 35 times a year	31/12/2005	-	-	-
	1-hour mean	350 $\mu g/m^3$ not to be exceeded more than 24 times a year	31/12/2004	1-hour mean	350 $\mu g/m^3$ not to be exceeded more than 24 times a year	2005 [(a)]
	24-hour mean	125 $\mu g/m^3$ not to be exceeded more than 3 times a year	31/12/2004	24-hour mean	125 $\mu g/m^3$ not o be exceeded more than 3 times a year	2005 [(a)]

Source: modified from DEFRA (2001, 2003b)

Note: (a) EU First Air Quality Daughter Directive (EUROPA, 2005a, 2005b)
(b) EU Second Air Quality Daughter Directive (EUROPA, 2005a, 2005c)
(c) O_3 not included in regulation for the purpose of local air quality management, but it is for the national objectives for protecting human health (DEFRA, 2001)
(d) EU Third Air Quality Daughter Directive (EUROPA, 2005a, 2005d)
* The 'stage 2' particles limit values for 2010 are indicative limit values, to be reviewed in 2004.
The conversion from ppm or ppb to mg/m^3 or $\mu g/m^3$ at 20°C and 1013 mb.

2.2.3 Monitoring of air quality

The consideration of levels of pollutants in the air for the review and assessment processes concerns monitoring and/or modelling as the assessment tools. In the UK, monitoring locations are broadly classified into five types: Urban, Suburban, Rural, Remote, and Special (DETR, 1998a). The "Urban" type is the station located in urban area such as London. The "Urban" type is further divided into five sub-categories: Kerbside, Roadside, Urban centre, Urban background, and industrial (DETR, 1998a). The definition of each type is as shown in Table 2.2.

Table 2.2 Monitoring location in the UK

Site type	Description
Kerbside	Location is within 1 m of the edge of a busy road. Local traffic is the main source of pollution. The objectives are to identify vehicle pollution hot spots, to assess worst case scenario, to evaluate impacts of vehicle emission controls, and to determine impact of traffic planning schemes.
Roadside	Located between 1 to 5 m of the kerbside of a busy road and the back of the pavement. Typically this will be within 5 m of the road, but could be up to 15 m. Local traffic is the main source. The station's objectives are to assess worst case population exposure, to evaluate impacts of vehicle emission controls, and to determine the impact of traffic planning scheme.
Urban centre	An urban location representative of typical population exposure in towns or city centres e.g. pedestrian precincts and shopping areas. This is likely to be strongly influenced by vehicle emissions, as well as other general urban sources of pollution. The pollutant sources are vehicle, commercial and space heating. The objectives are to identify long-term urban trends, to assess the exposure of large number of people.
Urban background	Station is some distance from sources and broadly representatively of city-wide background conditions. The station's objectives are to assess the exposure of a large number of people, to assess trends, to assess urban planning, etc.
Industrial	Located in an area where industrial sources make an important contribution to the total air pollution burden. The sources of pollutants are from industrial operations. The station's objectives are to assess the local impacts on health and amenity, to assess process optimization, to identify sources, to provide model input data, etc
Suburban	A location type situated in a residential area on the outskirts of a town or city. Source influences are the traffic, commercial, space heating, regional transport, urban plume downwind of a city. The station objectives are for the traffic and land-use planning, investigating urban plumes.
Rural	Rural is a site situated in an open country, in an area of low population density, distanced as far as possible from roads, populated and industrial areas. Source influences are the regional long-range transport, urban plume. The station objectives are for the ecosystem impact studies, assessing compliance with critical loads and levels for crops and vegetation, investigating regional and long-range transport, and identification of ozone 'hot spots'.
Remote	Location is in an open country, in an isolated rural area, experiencing regional background pollutant concentrations for much of the time. Source influences are regional/hemispheric background. The objectives of the site are for assessing 'unpolluted' global or hemispheric background conditions, long-range transport studies and long-term baseline trend analysis.
Special	Any special source-orientated or location category covering monitoring undertaken in relation to specific emission sources such as power stations, car parks, airports or tunnels.

Source: DETR (1998a); DEFRA (2003a)

The Department for Environmnet, Food and Rural Affairs (DEFRA, 2003a) recommended that the criterion for monitoring sites is that it should be in as open a setting as possible in relation to surrounding buildings. Immediately above the site should be open to the sky, with no overhanging trees or buildings. The sampler intake should be no higher than 10 m above local ground level and ideally between 1.4 m and 4 m. For urban centre or background sites, there should be no major sources of pollution within 50 m e.g. a large multi-storey car park. There should be no medium sized sources within 20 m, e.g. petrol stations, ventilation outlets from catering establishments etc. Cars/vans/lorries should not be expected to stop with their engines idling within 5 m of the sample inlet. The site should not be within 30 m of a very busy road (>30,000 vehicles/day), 20 m of a busy road (10,000-30,000 vehicles/day), 10 m of any other road (<10,000 vehicles/day). The surrounding area, within 100 m, should not be expected to undergo major redevelopment, so as to avoid disruption and to allow long-term trends to be followed. For traffic related sites, the site should be within 1 m of the kerb (kerbside sites). The site should be within 1-5 m of the kerb (roadside sites). For industrial sites, where specific sources are being targeted, monitoring should be carried out at the point of maximum impact as determined by modelling.

The air quality information observed on behalf of Department for Environment, Food and Rural Affairs (DEFRA) is based on results from 118 automatic monitoring systems (24 sites in Greater London area), which take readings every hour and in addition to these, there are around 1500 non-automatic monitors, which sample air pollution levels on a daily, weekly or monthly basis (DEFRA, 2004a). In general they monitor particulates, CO, NO_2, SO_2, and ground-level ozone. However, not all stations monitor all these pollutants, and some monitor other pollutants in addition to those mentioned, e.g. benzene, 1, 3 butadiene.

The recommended methods for making measurements of pollutants at monitoring sites are shown in Table 2.3. The measurement methods are categorized into two grades. The first grade is the method for the screening assessment, and the second grade is for the detailed assessment.

Table 2.3 Recommended methods for making measurements of pollutants in the UK

Pollutants	Screening assessment	Detailed assessment
Benzene	- Pumped sampling device on to a sorbent cartridge. Analysis is carried out by gas chromatographic determination. - Diffusion tubes	- Photo ionization detector based instruments
1,3 Butadiene	- Pumped sampling device on to a sorbent cartridge. Analysis is carried out by gas chromatographic determination.	- Photo ionization detector based instruments
CO	- Portable electro-chemical CO analyzers	- Automatic infra-red analyzers
Lead	- Sampling by filter based gravimetric method. Analysis is by atomic absorption spectroscopy or inductively coupled plasma mass spectrometry.	- Sampling by filter based gravimetric method. Analysis is by atomic absorption spectroscopy or inductively coupled plasma mass spectrometry.
NO_2	- Diffusion tubes or portable monitors - Electrochemical cell analyzers	- Automatic chemiluminescent analyzers (recommended) - Remote optical/long-path analyzers
O_3	- N/A	- UV Absorptionmetry [(a)]
PM_{10}	- Gravimetric samplers or portable monitors - Portable light scattering devices (with properly calibration)	- Gravimetric monitoring or automatic fixed-point monitors (TEOM, and ß-attenuation instruments). TEOM or ß-attenuation instrument should be adjusted by multiplying the data by 1.3 to estimate gravimetric equivalent levels.
SO_2	- Active samplers (bubblers) or portable monitors - Electrochemical cell analyzers	- Automatic ultra-violet fluorescent analyzers (recommended) - Remote optical/long-path analyzers

Source: modified from DEFRA (2003a)

Note: N/A = not available

(a): AEA Technology (1997), O_3 is not included in LAQM but it is a pollutant in national air quality objectives and measured at automatic air quality monitoring network through out the UK

2.2.4 Air quality modelling

Air quality models are valuable tools for air quality review and assessment. A number of air quality models have been used in the UK for academic purposes and regulatory purposes. Some were developed under UK conditions. Some are imported from U.S.A., and other European countries. Air quality models in the UK are categorized into three classes as (1) a screening model, (2) an intermediate model, and (3) an advanced model. The models, which have been in common usage within the UK over recent years (DEFRA, 2000), are shown in Table 2.4 and are detailed in Chapter 3. The use of air quality models for regulatory purposes have probably been expanded in the UK since 1998 due to the introduction of local air quality management (LAQM), which local authorities in the UK were required under Part IV of the Environment Act 1995 to carry out periodically involving a review and assessment of air quality in their areas. They were guided in their use of screening models in the second stage of

the first round review and assessment, and in the updating and screening assessment in the second round. Advanced models were recommended for the third stage of the first round review and assessment, and in the detailed assessment of the second round.

Table 2.4 Air quality models common usage in the UK

Model type	Model name	Origin
Screening	ADMS-SCREEN, D1 Stack Height Calculation, DMRB, GRAM, GSS	UK
	CAR	Europe
Intermediate	AEOLIUS, ALMANAC, R91	UK
	COMPLEX-1, ISC-SCREEN	U.S.A
	OSPM	Europe
Advance	ADMS	UK
	AAQUIRE, AERMOD, BREEZE ROADS, CALINE, ISC, PAL, RTDM	U.S.A
	INDIC AirViro, Fluidyn-PANACHE, TRAQS	Europe

Source: modified from DEFRA (2000)

2.3 Air quality assessment methodologies in Thailand

2.3.1 Air quality review and assessment

To date, environmental quality management in Thailand is carried out under the Enhancement and Conservation of National Environmental Quality Act, B.E. 2535 (hereafter called as NEQA 1992) (NEQA, 1992). Air quality review and assessment in Thailand is a step in preparing the action plans for the reduction and eradication of pollution in pollution control areas, which is a top-down process from central government agency to local authority. NEQA 1992 Part 3 Section 59 gives a power to the National Environment Board, chaired by the Prime Minister, to declare a pollution control area in cases when it appears that any locality is affected by pollution problems, and there is a tendency that such problems may be aggravated to cause health hazards to the public or adverse impacts on the environmental quality. NEQA 1992 Section 60 requires the local official in the locality designated as the pollution control area, to prepare and submit an action plan for reduction and eradication of pollution in such area to the Provincial Governor in order to incorporate such plan into the Provincial action plan for environment quality management. In preparing the local action plan for reduction and eradication of pollution, the following steps need to be taken (NEQA, 1992):

(1) to survey and collect data concerning point sources of pollution located within the limits of that pollution control area.

(2) to make an inventory showing the number, type and size of point sources of pollution under survey and collection of data according to (1) above.

(3) to study, analyse and assess the state of pollution, as well as the scope, nature, severity of the problem and impacts on environmental quality in order to specify suitable and necessary measures for mitigation and eradication of pollution in that pollution control area.

It is the duty of the Provincial Governor, in which there is a locality designated as environmentally protected area, or as pollution control area, to formulate a provincial action plan for environmental quality management at provincial level and submit it to the National Environment Board for approval within one hundred and twenty days from the date on which the Governor of that province is directed by the National Environment Board to prepare the provincial action plan for environmental quality management. If it is deemed reasonable, NEQA 1992 Part 3 Section 58 gives a power to the Provincial Governor to prescribe a special set of emission or effluent standards applicable to the pollution control area, higher than the national standards or the standards set by virtue of other law which remains in force.

Since 1992, the National Environment Board has declared 16 areas in 11 provinces as pollution control areas (MNRE, 2004). Four areas are situated in the lower south of the country, six in the upper south, one in the east, and five in suburbs of Bangkok. The last pollution control area was declared in 1996. Most measures concern water pollution and solid waste management (PCD, 2004f). Even though, Bangkok has not been declared as a pollution control area, the local government of Bangkok declared 1999 as the Air Pollution Mitigation Year and implemented a number of measures (APMA, 2002). Very recently, the Klong Tuey District in Bangkok was designated as an environmentally protected area (PCD, 2004g) for three years in order to protect the pollution from the storage and transport of the chemical and hazardous substances in Klong Tuey Habour (Ministerial regulation, 2003).

2.3.2 Air quality standards and objectives

The Air Quality Standards in Thailand were set under the requirements of the Enhancement and Control of National Environmental Quality Act B.E. 2535 (NEQA 1992). The present standards as shown in Table 2.5 are prescribed under the Notification of National Environmental Board No.10 published in 1995, which covers seven pollutants: CO, lead, NO_2, O_3, SO_2, PM_{10} and total suspended particulate (TSP), and state the reference means, and the concentrations (PCD, 2000b), but the objectives to be achieved or the target date have not been set. This notification also sets the standard methods for measuring air pollutants as shown in Table 2.6.

Table 2.5 Air Quality Standards in Thailand

Pollutant	Air Quality Standards in Thailand	
	Reference mean	Concentration
CO	1-hour mean	34.2 mg/m^3 (30 ppm)
	8-hour mean	10.3 mg/m^3 (9 ppm)
Lead	1-month mean	1.5 $\mu g/m^3$
NO_2	1-hour mean	323.9 $\mu g/m^3$ (170 ppb)
O_3	1-hour mean	200 $\mu g/m^3$ (100 ppb)
SO_2	1-hour mean	780 $\mu g/m^3$ (300 ppb)
	24-hour mean	300 $\mu g/m^3$ (120 ppb)
	Annual mean*	100 $\mu g/m^3$ (40 ppb)
PM_{10}	24-hour mean	120 $\mu g/m^3$
	Annual mean*	50 $\mu g/m^3$
TSP	24-hour mean	330 $\mu g/m^3$
	Annual mean*	100 $\mu g/m^3$

Source: PCD (1999a)

Note: The conversion from ppm or ppb to mg/m^3 or $\mu g/m^3$ at 25°C 1013 mb.

* Geometric mean

Meanwhile, air quality management in Thailand is carried out under the pollution, prevention and mitigation policy in accordance with the policy and perspective plans 1997-2016 (B.E. 2540-2559) under the Enhancement and Conservation of the National Environmental Quality Act B.E 2535 (NEQA 1992). This policy sets the target goal that each regulated pollutant will be within its standard throughout the target period (PCD, 2004c).

2.3.3 Monitoring of air quality

Air quality monitoring stations in Thailand are broadly classified into two types: "roadside" and "general" stations. The "roadside" stations are located within 2-5 m from the edge of the main road. The "general" stations are located within 50-100 m from the edge of the main road in an area of typical population exposure (PCD, 2000b). Additionally, one-week measurement at the kerbside of some main roads in Bangkok is carried out annually.

Thailand has established an extensive air quality monitoring network operated by Pollution Control Department (PCD) with the aim of providing update information on major air pollutants. Thailand commenced air quality monitoring in 1983 (PCD, 2004d). The monitoring network has progressively evolved and expanded to cover a variety of pollutants and meteorological parameters. The majority of sites monitor particulates, CO, NO_2, SO_2, and ground-level ozone. Meteorological parameters including wind speed, wind direction, temperature, pressure, rain, relative humidity, solar radiation are also measured at many of the monitoring sites, which increases the capability to analyze the pollution situation. However, not all stations monitor all these pollutants and meteorological factors, and some monitor other pollutants in addition to those mentioned, e.g. total hydrocarbon (THC). The primary responsibility for monitoring rests with the PCD. Its monitoring network currently consists of 71 monitoring sites nationwide, which are linked to PCD's central computer system located in Bangkok. To date, there are 21 permanent stations in Bangkok run by the PCD and one station operated by the Bangkok Metropolitan Administration (BMA) (PCD, 2004d). Under the decentralization process mandated by the new Constitution, BMA and other city governments will progressively assume responsibility for air quality monitoring functions, while policy making and standard setting will continue to remain the responsibility of national level agencies, such as the PCD.

The measurement methods for air pollutants are shown in Table 2.6. The methods are categorised into two grades as the standard method and equivalent method, which are stipulated under the Notification of National Environmental Board No.10 published

in 1995 and Notification of Pollution Control Department published in 2003 respectively.

Table 2.6 Methods for making measurements of pollutants in Thailand

Pollutants	Standard method [1]	Equivalent method [2]
CO	- Non-Dispersive Infrared (NDIR)	-
Lead	- Gravimetric High Volume and analysis is carried out by the atomic absorption spectrometer	-
NO_2	- Chemiluminescence	-
O_3	- Chemiluminescence	- Ultraviolet Absorption Photometry
PM_{10}	- Gravimetric	- Beta Ray - Tapered Element Oscillating Microbalance (TEOM) - Dichotomous
TSP	- Gravimetric	-
SO_2	- Pararosaniline for 24 hr mean and annual mean	- Pararosaniline for 1 hr mean - Ultraviolet Fluorescence for 24 mean

Source: (1) National Environmental Board (1995)
(2) PCD (2003b)

2.3.4 Air quality modelling

The application of air quality model in Thailand seems to begin its history about three decades ago. Around 1973, Pescod and Rosales (1973) used the theory of gas diffusion to estimate the concentrations of CO and particulate matter at some dense traffic roads in Bangkok. This theory was also applied to evaluate the CO levels from road transport in the Had-Yai district, Songkla Province (Youyuunyong, Nopparatkrirad and Chewasettathum, 1991). The theory of Gaussian dispersion modelling was applied to predict the concentrations of SO_2 around the Mae Moh Power Plant, a pulverized lignite fired steam power plant, in Lampang Province (Wangwongwatana, 1980; Ditthawisan, 1995). The use of computer-based air models probably began around 20 years ago, during the course of the environmental impact assessment for the Mae Moh Power Plant (Air and Waste Management Association, 2004). The computer-based air quality models, commonly used for predicting air quality in Thailand, are the HIWAY model (Chongvisal and Limpaseni, 1983; MOI, No date; Kamonwat, 1994; MOTC, 1998), the later version, the HIWAY-2 model (MOI, 1988), the CAL3QHC model (ADB, 1997), the CALINE-4 model (ADB, 1997; Sripraparkorn, 2001; Sripraparkorn, Jinsart and Hooper, 2003), the Swedish

Indic-AirViro system (TEI, 1994; PCD, 2000a, 2004e), the CRSTER model (Soontrapa, 1989), the VALLEY model (Soontrapa, 1989; ADB, 1997), the CALPUFF model (Doolgindachbaporn, 1995; Harvey, No date), the ISC-2 model (ADB, 1997), the ISC-3 model (Harvey, No date), the ISCST model (Jearaphasuarnun, 2002; Pummakarnchana, 2002), the PTPLU model (ADB, 1997) and the UK-ADMS model (Harvey, No date). Meanwhile, the advanced models such as the Lagarangion Particle Model (LPM), the Models-3/Community Multiscale Air Quality (CMAQ) model, and the MM5 model, have being studied for the applicability to the environmental conditions in Thailand (Air and Waste Management Association, 2004). The models mentioned above have been grouped into types of screening and advanced models together with their origins, as shown in Table 2.7.

Table 2.7 Air quality models common usage in Thailand

Model type	Model name	Origin
Screening	CAL3QHC, HIWAY/HIWAY-2, VALLEY, PTPLU	U.S.A.
Advance	ADMS	UK
	CALINE4, ISC, CALPUFF, CRSTER	U.S.A
	Indic AirViro	Europe

2.4 Discussion

The process of the review and assessment of air quality in the UK and Thailand are different both spatially and temporally. The UK Environment Act 1995 specifically requires all local authorities to regularly review their local air quality with the recommendation of what to do and the scope of how to conduct, while the Thai Enhancement and Conservation of National Environmental Quality Act, B.E. 2535 (NEQA 1992) requires the local authority in the area, that is declared by the National Environment Board as a pollution control area, to conduct a review and assessment of the environmental pollution occurring in the designed pollution control area. The requirement in NEQA 1992 does not specify the air quality review and assessment.

The process of the air quality review and assessment in the UK begins at the local authority level in order to investigate whether the problem is serious. If air quality objectives are not met, the local authorities must declare AQMAs and prepare action plans to improve the air quality. In this regard this process can be viewed as a bottom-up process. The bottom-up process requires a lot of management resources, e.g.

manpower (e.g. officials, environmental expert), financial resources, tools (e.g. air quality monitoring, air quality model), and management time. However the protection of health threat is assured in advance. The environmental review and assessment system in the Thailand is a top-down process. National Environmental Board declare a Pollution Control Area (PCA) in an area which appears to have pollution problems. Then, the local authority in PCA prepare a local action plan. One probable reason is that the management resources for mitigating pollution problems in Thailand are limited, especially in the case of air pollution. One of the limited resources in air quality management in Thailand is the availability urban air quality models, which are developed under the environmental conditions of the country. The urban air quality models applicable in Thailand are generally the models developed in the USA and Europe.

Ambient air quality standards for the UK and Thailand similarly regulate CO, NO_2, O_3, lead, PM_{10}, and SO_2. The total suspended particulate matter (TSP) is included in Thai standard but not in that of the UK. TSP is included in Thai standards, because coarse particles are one of the main air pollutants. There are two more pollutants: benzene, and 1, 3 butadiene, which are included in the UK standards but not in the Thai standards. So far, the Pollution Control Department (PCD) has been studying the standard for benzene in ambient air (Rungruksatum, 2000). Therefore the benzene standard will be included in Thai standards in the future. Meanwhile, PCD also conducted a study in order to establish the air quality standard of $PM_{2.5}$ (PCD, 2004h). Air quality standards in the UK are not only under the national regulation, but also under EU laws, whereas standards in Thailand are under national control basis only. The Asian member country should establish cooperation on air quality limit values like those in the EU community because a lot of air pollutants causes trans-boundary pollution from one local area to neighbouring areas, or from one country to other countries. For example acid rain in Europe and the haze event in Asian countries from the forest fires in Indonesia illustrate cases. The date when standards should be achieved is not defined in Thai ambient air quality standards unlike those in the UK air quality standards and EU Air quality framework and Daughter directives. It is a good strategy to have a deadline for assessing the

effectiveness of mitigation measures. The target date should be included in Thai ambient air quality standards in the future.

Unlike those in the UK, air quality monitoring sites in Thailand do not cover the locations in rural and remote areas. This brings a lack of the baseline data in the country's air quality, its trends and the annual/seasonal variations. To date, the number of national automatic air quality monitoring sites in London and Bangkok is similar, 24 and 22 sites respectively, but the total number of the monitoring sites both the automatic and non-automatic in the local and national networks in the UK is much greater than those in Thailand. However, air quality monitoring sites in Thailand have monitored meteorological parameters, which are very helpful to increase the capability to analyse and predict the pollution situation, whilst the meteorological parameters have not been monitored at air quality monitoring sites in the UK.

To review and assess air quality in the UK, the various measurement methods are allowed separately for the screening stage and the detailed stage. The UK Government's recommendation gives a lot of alternative ways to those who want to conduct air quality review and assessment, especially the recommended methods at the screening stage, when much less management resources are used than in the measurement methods for the detailed stage. In the case of Thailand, air quality review and assessment for regulatory purposes have to follow the regulated measurement methods, which most methods, in both the standard and equivalent methods, fall into the detailed measurement method category compared the UK recommended measurement methods. This means the screening operation of air quality review and assessment has not had a formal platform in Thailand. To date the measurement of all air pollutants under the regulated methods are undertaken by central government agencies (e.g. Pollution Control Department), Bangkok Metropolitan Administration (BMA) and a few environment consultancy firms.

A larger number of air quality models have been applied in the UK than in Thailand. Air quality models used in the UK are from several sources including the models developed under UK environments. Almost all air quality models developed in the

UK are in the types screening and intermediate, which are recommended to use in the screening stage of air quality review and assessment. Most air quality models used in Thailand are from USA. The popularity of the USA air quality models in Thailand results from their availability to public. It appears that most of the air quality models used in Thailand are of the advanced type, and a few number are of the screening type, which none of them was developed under Thailand conditions. The review on the measurement method and the application of air quality models suggests that the screening assessment is disregarded in air quality review and assessment in Thailand.

2.5 Summary

The system of air quality review and assessment in the UK represents an example of best practices and can be considered by Thailand to improves its own procedures for conducting air quality review and assessment. In the UK the role of local authorities is in the front line of air quality review and assessment process. The UK also has a well developed system of air quality standards with target dates. A further aspect that could be incorporated in Thailand would be to include air quality monitoring in rural and remote areas. Other areas where the UK experience could be transferred to Thailand includes the use of measurement methods of air pollutants for the screening stage, the application of screening air quality model, and the development of air quality model to take into account the country's specific conditions.

Chapter 3
A Comparative Evaluation of Air Quality Models for Assessing the Impact of Road Transport on Air Quality in London and Bangkok

3.1 Introduction

This chapter presents details on atmospheric dispersion theory, the applications of urban air quality models and use of screening models for air quality review and assessment in the UK. This chapter also discusses the selection of models developed or used in the UK which have the possibility to be modified for applicable in Bangkok, the evaluation of selected model performance in London and Bangkok, and the possibility to alter the models to fit the conditions in Bangkok. One of the objectives, therefore, is to select a model that has the potential to be modified to become an air quality model for Bangkok.

3.2 Atmospheric dispersion theory

A dispersion model is a series of equations, which describes the relationship between the concentration of a pollutant in the atmosphere arising at a chosen location, and the emission rate, and factors affecting the dispersion and dilution in the atmosphere (DETR, 1998b). Air quality models need to incorporate a standard dispersion model (Highways Agency, 1999) for predicting pollutant dispersion. Most air quality models are based on Eulerian or Lagrangian approaches. Many assessment models incorporate simplified analytical solutions to the more complete numerical formulations or employ empirical relationships. The following section provides a brief overview of the main modeling approaches.

3.2.1 The Eulerian or grid model

This type of model is based on the mass conservation of pollutant inside a box, which generally presents a large area such as a city (Zannetti, 1990). The area under investigation is divided in grids, both in the vertical and in horizontal direction (Builtjes, 2000). The limitations of this model (Nagendra, and Khare, 2002) arise from employing the K-theory diffusion equation, which is valid only if the size of the plume or puff of pollutant is greater than the size of the dominant turbulent eddies.

The K-model assumption is also not valid for the convective boundary layer under strong instability. The other limitations are the requirements of large computational costs in terms of time and storage data, and large amount of input data. An example of the Eulerian model is the Danish Eulerian Model (DEM) (Havasi and Zlatev, 2002). The DEM is a large-scale model, in which the space domain of the model contains the whole of Europe together with parts of Asia, Afica, and the Atlantic Ocean. It was used to estimate the contributions from SO_2, NO_x, VOC, and NH_3 emissions in the other European countries to pollution level in Hungary.

An alternative model often used in order to deal with a small set of grid cells is the "box model" (Sportisse, 2001). It is the simplest and probably the most robust (NSCA, 2000) form of a dispersion model for assessing multi-source impacts (Elsom, 1998). The model calculates the changes in concentration in a finite box of air as the balance between material flowing into the box and that flowing out, with an allowance for any emission occurring within the box (Highways Agency, 1999). The model mainly relies on an assumption of a perfectly stirred reactor (Sportisse, 2001), thus air pollutants within the box are assumed to be thoroughly mixed. The model is employed for estimating the average concentration from multiple low-level area sources assumed evenly spread over the ground surface area of the box (Elsom, 1998).

Sportisse (2001) investigated the justification of one-box models in a one-dimensional scale. He pointed out that high errors in the models may occur due to the non-linearity of atmospheric chemistry. Nonetheless, several studies found that the box models gave good agreement with the measurements. For example, the estimate of instantaneous hazardous dense-gas releases by the box models: SLAB, BOX, and DENS1 models (Gudivaka and Kumar, 1990). Jorquera (2002) used box models for assessing air quality at Santiago, Chile. Because of the simplicity of the box model, it is widely employed in developing air quality models, for instance in the Boxurb model (Middleton, 1998), or in combination with a Gaussian dispersion model such as the OSPM model (the Danish Operational Street Pollution Model). The OSPM is a street canyon model, in which the direct road contribution is calculated by applying

the Gaussian plume dispersion theory, while the circulation contribution is derived by a box model algorithm (Vardoulakis, Gonzalez-Flesca, and Fisher, 2002).

3.2.2 The Gaussian model

This model applies the standard deviations of the Gaussian distribution in two directions: the y-axis in the horizontal direction and z-axis in the vertical direction, to represent the dispersion of pollutants downwind of its origin (Canter et al, 2000) in a cone-shaped plume. The dispersion of pollutants from the plume centre-line follows a normal bell-shaped curve, which the high concentration lies towards the centre of the plume and lower concentration lies towards the edges (Elsom, 1998). A number of assumptions are used for this model. First, the analysis assumes a steady state system. Second, the diffusion in the x-axis direction is ignored, while transport in this direction is accounted for by advection depending on wind speed. Third, the plume is reflected at the ground rather than deposited, according to the rules of mass conservation. Fourth, the model applies to an ideal aerosol or an inert gas. Finally, the calculations are only valid for wind speeds greater than or equal to 1 m/s (Canter et al, 2000). The Gaussian model was originally used for predicting concentrations from point sources, and later extended to line sources and area sources.

The Gaussian equation is the most widely employed method for modelling the dispersion of pollutants from sources. This can be seen from the previous USEPA "Guideline on Air Quality Models" (Canter et al, 2000). In that guideline, the USEPA summarized the performance of models in several comparative analyses and suggested the best application of the models. The models that performed well for a general set of conditions were classified as "Appendix A models", which comprised 19 models. Models not classified as "Appendix A models", but recognized as having potential application for a specific case were designed as "Appendix B models". Of the 19 models in the "Appendix A models", only two of them were not Gaussian-based model. The examples of Gaussian-based models used in the UK air quality management are the GRAM, ISC, and CALINE4 models.

Gaussian theory in combination with another dispersion model was also found to be useful. For example, the Danish Operational Street Pollution Model (OSPM) is based

on both the Gaussian and the box dispersion theories. The development of the USEPA CALINE2 model was also based on the Gaussian plume theory together with concepts of a box model (Sharma, and Khare, 2001).

3.2.3 The Lagrangian model

The Lagrangian model is a mass conservation model. The model is different to the Eulerian model because the Eulerian box does not move, while in the Lagrangian model, an air parcel is followed along the average wind trajectory (Zannetti, 1990; Highways Agency, 1999). In the model, it is assumed that an air parcel keeps its identity during its path along the trajectory (Builtjes, 2000). Because the model can simulate the effects of complex wind patterns, it is considered to provide more accurate pollution estimates than the Gaussian and empirical models (Highways Agency, 1999).

The Lagrangian approach is used in air quality modelling at both local and regional scale. Lee and Kingdon (2001) employed a 10-layer Lagrangian acid deposition model to estimate long term trends in UK sulphur deposition. The Lagrangian dispersion model NAME developed by the Meteorology Office, in the UK has been run over a regional scale for 1996 to predict sulphate and nitrate aerosol imported to the UK from Europe (Redington and Derwent, 2002). The NAME model has been used successfully to assess the impact of routine atmospheric radioactive discharges from the Sellafield nuclear installation (Nelson, Kitchen, and Maryon, 2002). The Lagrangian model GRAL and a Gaussian finite line source dispersion model CAR-FMI performed well when they were tested against a roadside data set under low wind speed conditions (Oettl et al, 2001). The GRAL model simulated better at the cases of low wind speed and those with the wind nearly parallel to the road.

3.2.4 The empirical model

The empirical models have been developed empirically, from analysis of air pollution data in relation to measured meteorological, traffic, site layout, and other relevant variables. These models can give accurate results under sufficient data for thorough statistical analysis. However, these are applied strictly only to the location at which the measurements take place, and there is considerable uncertainty if they can be

extrapolated beyond the range of the data on which they were based. These are, therefore, of limited use in making pollution forecasts for future years when vehicle emission characteristics will be very different (Highways Agency, 1999). Limitations (Nagenda and Khare, 2002) of empirical model include the requirements of long historical data sets, the lack of physical interpretation, and the inability to provide information about how pollutant levels would respond to emission controls. However, the empirical model was widely used in air pollution modelling, especially in the prediction of NO_2 from NO_x (i.e. Dixon, Middleton, and Derwent, 2000, Stedman et al, 2001). Other examples of empirical models include CAR International and DMRB.

3.2.5 The new generation dispersion models

At present, a new generation of the dispersion models take account of turbulence and diffusion replacing the Gaussian assumption with alternative representations and understanding of atmospheric processes of the turbulence and diffusion, which vary significantly with height rather than assume it is uniform (Elsom, 1998). The new generation of the dispersion models adopts a more sophisticated approach to define vertical profiles of turbulence, and modifies the Gaussian distribution under more convective (unstable) conditions. The new models were expected to represent the atmosphere in a more realistic way (DETR, 1998b). The examples of this type of model are the UK-ADMS model and the USEPA-AERMOD model.

3.3 The application of urban air quality models in the UK

Air quality models vary from advanced models reliant on high capacity computers and expert users, through to simple models which could be run on PC computers and to simpler methods requiring only the use of a nomogram and a workbook or spreadsheet. Generally, dispersion models have two levels of sophistication: screening models, and refined models (Canter et al, 2000) or more detailed models (Highways Agency, 1999). The latter are sometimes divided further into two subgroups of intermediate and advanced models (DETR, 1998b).

The simpler methods are often referred to as "screening methods". Screening models provide a preliminary level of assessment, which have been employed to determine

whether there is a problem, which needs a more detailed air quality model in the assessment (Elsom, 1998). The models require simple input data, consider only one source at a time, and tend to be restricted to one type of source. Screening models usually require no meteorological input and therefore could not take account of local conditions. Screening and intermediate models might be the most appropriate when the meteorological data lack reliability and accuracy, which would warrant the use of more sophisticated models. Most screening models take a few minutes to work out a simple scenario. The models are not expensive. Thus, they provide a very useful way of gaining quickly and cheaply a preliminary air quality assessment (DETR, 1998b).

Intermediate models are mainly computer-based models, in which factors affecting the dispersion pathways have been simplified, but not to the same extent as for screening models. The models require more information about the source than screening models. They could take an account of varying meteorology, and they might be treat more than one type of source (DETR, 1998b). Advanced models could provide the results more accurately than screening and intermediate models, but only if detailed, meteorological and emission data sets are available. The models are able to treat more than one type of source. They are all multi-source models. The most advanced air quality models need very detailed meteorological inputs, and may require a workstation or a powerful PC to run (DETR, 1998b). Their output choices are more versatile. Specific effects such as atmospheric photochemistry, complex terrain, and building effects could be taken into account. Some of the more advanced models incorporate the most up-to-date treatments of the meteorology of the atmosphere (DETR, 1998b).

Frequently used models: screening, intermediate, and advanced models, which have been in common usage within the UK over recent years (DEFRA, 2000) include the following.

3.3.1 Screening model

(1) ADMS-SCREEN

The ADMS (Atmospheric Dispersion Modelling System)-SCREEN model (DEFRA, 2000) is a reduced version of the ADMS-3 model. It predicts both maximum annual

mean and 1-hour concentrations at a distance from the stack. The prediction can include either building wakes or simple terrain effects. The meteorological conditions are in-built data sets, which can be selected from options. The ADMS-SCREEN model was employed in the local council districts such as Pendle Borough (Pendle Borough Council, No date), Suffolk Coastal (Suffolk Coastal District, 2000), and Mid Bedfordshire (Mid Beds District Council, 2000) for predicting air pollutants from industrial sources at stage 2 in an air quality review.

(2) CAR International model

CAR (Calculation of Air Pollution from Road Traffic) is a model designed for estimating traffic air pollution to support the implementation of air quality legislation in the Netherlands (CAR, 1993; DEFRA, 2000; Fisher, 2000c; UWE, 2002). It is a Gaussian based model. The formulae are based on wind tunnel experiments, theoretical considerations and monitoring. The model permits the calculations of CO, NO_2 and benzene, but does not deal with PM_{10}. However a user-defined air pollutant component can be added. However the output is in the form of annual averages and 98 percentiles of 1h, 8h and 24h average concentrations. Empirical conversion factors from these percentiles to those specified in the UK national air quality strategy are necessary. Recently, the CAR model was used by the SEIPH-ERG (South East Institute of Public Health, Environmental Research Group) in a review and assessment of air quality at stage three for the South Bucks District (SEIPH-ERG, 2000), and the London Borough of Wandsworth (Wandsworth Borough Council, No date.). In Wandsworth Borough, the AERMOD model and the ADMS-Urban model were also used to predict SO_2 and NO_2 from large point sources.

(3) DMRB model

The DMRB (Design Manual for Roads and Bridges) model was developed in an Excel spreadsheet format based on the DMRB model published by the Highways Agency in Volume 11, Section 3, of the Design Manual for Roads and Bridges "Environmental Assessment" (DEFRA, 2000; Fisher, 2000c; UWE, 2002). The model was derived from algorithms prepared by the Transport Research Laboratory (DETR, 1999: Stanger Science and Environment, 2002). The dispersion theory is based on a Gaussian model (Sharma and Khare, 2001). The model contains a method,

which enables major air pollutants around a road network to be estimated. The methods use a series of nomograms, such as those in the R91 model (Fisher. 2000c). However, the latest version, DMRB version 2, has been generalised to apply to roads in urban areas though it has been mainly used for screening new road schemes.

The model was designed following the procedures described in LAQM.TG4 (00) - Review and Assessment: Pollutant Specific Guidance for Local air Quality Management (Stanger Science and Environment, 2002). It is an example of an attempt to produce an accessible tool that non-experts can use. The current DMRB method includes methods for assessing concentrations in the form required by UK national air quality objectives (Fisher, 2000c). The model was widely used in air quality review and assessment stage two. Local authorities, such as Wokingham District Council (Wokingham Unitary, 2002), South Hams District Council (2001), Carlisle City Council (No date), Daventry District Council (No date), Gateshead Council (No date), Exeter City Council (2000), Wealden District Council (No date), East Hertfordshire District (2001), etc. used this model as a tool in their review and assessment.

(4) DI Stack Height Calculations

The model (DEFRA, 2000; UWE, 2002) estimates a chimney height by ensuring that the ground level concentration of a pollutant does not exceed a specified standard for more than about 5 minutes under weather conditions which are likely to occur 98% of the time. The method does not take into account worst-case meteorology. It is regarded as a guide for estimating a chimney height rather than an accurate definition of the discharge chimney height. It is applicable as a check whether the smaller emitting processes, which come under local authority control, have stacks of adequate height.

(5) GRAM model

The GRAM model (University of Greenwich's Review of Air Quality Method) is a screening model used for predicting the urban background and roadside concentrations for averaging times needed in the UK Air Quality Objectives (DEFRA, 2000; Fisher, 2000c). The model also includes the prediction with canyon-

like streets in urban areas. The model is a screening model intended to produce the worst case concentration by assuming worst case meteorology. Future scenarios are easily calculated (Fisher, 1998a). The model is based on algorithms used in the R91 model for urban dispersion and the USEPA CALINE4 model for roadside dispersion (Fisher and Sokhi, 2000). The GRAM model was used at stage two of air quality review and assessment for predicting the impacts of road transport in the London Borough of Barnet (1998; Crabbe, Beaumont, and Norton, 2000). It was employed to investigate roadside concentrations in busy streets in the UK and France, and compared with the measurements (Fisher and Sokhi, 2000).

(6) GSS

The GSS (Guidance for Estimating the Air Quality Impact of Stationary Sources) model was developed by the Environment Agency in 1998 as a guidance providing pollution concentration from stack emissions (DEFRA, 2000). It expresses as nomograms based on large number of computations using in the ADMS model. The GSS model covers ten stack heights, four categories of surface roughness, three averaging times and three climate types. The results are comparable with the prescribed air quality objectives. The use is limited to a range of stack height and exit velocities, and cannot treat building wake effects or non-buoyant source releases. Previously, the GSS model was used at the second stage of air quality review and assessment for calculation of concentrations in the vicinity of point sources of pollution in the district of Arun District Council (2000).

3.3.2 Intermediate models

(1) AEOLIUS

The AEOLIUS (Assessing the Environment of Locations in Urban Streets) model is designed for predicting the highest exposures to traffic emissions in street canyons (DEFRA, 2000; UWE, 2002). The model was developed the UK-Met Office (2005). The model estimates the hourly mean concentrations of NO_x, NO_2, CO, SO_2, PM_{10}, benzene, and 1,3 butadiene. The model can make use of hourly traffic data over a week. Emission factors must be defined by the user. It requires sequential hourly meteorological data, and can process data up to one month at a time. A field study on CO was conducted in a busy street canyon in Leek, Staffordshire (Manning et al,

2000). The findings show that the ability of a model to calculate the correct trends in CO concentration was dependent on wind direction. It could not reproduce the peaks in hourly pollution that were measured within the street canyon, but the estimates were all within an order of magnitude of the observations. The estimates of CO concentration were heavily dependent on traffic data. The model was found to be most sensitive to vehicle emissions. The AEOLIUS and DMRB models were used in the first stage review and assessment in the Borough of Chelmsford (Chelmsford Borough Council, No date). There was a large discrepancy between the two models. The mean values obtained from NO_2 diffusion tubes were within the range of the DMRB model rather than the AEOLIUS model.

(2) ALMANAC Model

This model was developed by the Central Electricity Generating Board (CEGB), in order to establish and confirm that the stack heights being recommended in new designs would ensure adequate dilution and dispersion (DEFRA, 2000; Fisher, 2000c; UWE, 2002). The particular feature of this work is that it is able to investigate a wide range of meteorological conditions and takes into account the variability of the atmosphere, which is particularly important for describing dispersion from high-level sources. It has been used widely by the power generators in their recent applications to build gas-fired power stations in the UK. The model normally treats only a single stack. Many of the ideas in the model have later been applied in the ADMS model. Both the highest hourly concentration and the annual average concentration can be calculated using the model. One particularly valuable feature is that the model allows the user to calculate 98 percentiles (the hourly concentration not exceeded on more than 2% of occasions), which is useful when applying European Directives (Bennett, 1989). It is not supported commercially by any organization.

(3) COMPLEX-1

The COMPLEX-1 is a USEPA complex terrain model for multiple point sources (DEFRA, 2000; UWE, 2002). It uses sequential meteorological data, but requires fewer parameters than the RDTM model. The model is now replaced by the RDTM model.

(4) ISC-SCREEN

The ISC (Industrial Source Complex)-SCREEN model is one of the USEPA models using worst-case meteorological data for a single point source, area or volume source, and can take account of building wake effects. It has a limited ability to treat terrain above stack height (DEFRA, 2000; UWE, 2002).

(5) OSPM

The OSPM (Operational Street Pollution Model) is a street canyon model on which the AEOLIUS model and the street canyon module in the ADMS-URBAN model are based (DEFRA, 2000). The model was developed at the Danish National Environmental Research Institute (Berkowicz et al, 1996). Concentrations in the street are estimated by adding the plume from vehicle exhausts to recirculaing exhaust gases in the street. The direct road contribution is calculated by applying a Gaussian plume theory, while the contribution of recirculation is estimated by a box model (Vardoulakis, Gonzalez-Flesca and Fisher, 2002). The model was used as a tool for the assessment of traffic-related air pollution in several studies (Berkowicz et al, 1996; Vardoulakis, Gonzalez-Flesca, and Fisher, 2002).

(6) R91 Model

The R91 model is a Gaussian-based model developed by a Working Group led by the National Radiological Protection Board (NRPB) in 1979 and recommended for use in the nuclear industry (DEFRA, 2000; Fisher, 2000c; UWE, 2002). The model is designed for use with low-level point sources, but behaves adequately for high-level point sources. The model has been used to determine the highest permissible discharge rates from stack arrangements, which ensures that the maximum ground-level concentrations comply with specified exposure levels. Both short-term (hourly) average concentrations and long-term (annual) average concentrations can be calculated. Formulae within the R91 model are stated explicitly and these have been used to build the relationships adopted within the GRAM model. The R91 model originally consists of nomograms, but a PC version called DISTAR is commercially available; other PC versions include STACK (encoded by Meteorological Office) and PLUMES (used by the Environment Agency).

3.3.3 Advanced models

(1) AAQUIRE model

The AAQUIRE model is a package, which incorporates a number of USEPA models which enables it to account for point, area, line and volume sources simultaneously (DEFRA, 2000; UWE, 2002). For example, the AAQUIRE 2000 uses the CALINE4 model for the dispersion of road traffic emissions and the AERMOD model for all other sources (West Wiltshire District Council, 2000). The system is able to predict concentrations as hourly values, and as percentiles, means and similar statistics. The model was used to predict NO_2 from vehicles on the A38 road, and PM_{10} from the industrial processes at stage 3 of a review and assessment in South Hams District Council (2001). It was also used by CES (Consultants in Environmental Sciences Ltd) to predict air qquality at stage 3 in the district of West Wiltshire (West Wiltshire District, 2000), and Waverley Borough (No date).

(2) ADMS model

The ADMS (Atmospheric Dispersion Modelling System) has been developed by the Cambridge based Cambridge Environmental Research Consultants Ltd (CERC) as an advanced dispersion model which takes into account the most up to date understanding of atmospheric dispersion (DEFRA, 2000; Fisher, 2000c; UWE, 2002). The model was developed in a modular form to deal with specific features including the ability to treat dry and wet deposition, building wake effects, complex terrain and coastal influences. The ADMS-3 model is a new generation model, allows for the use of point, area, volume and line sources, and can predict long-term and short-term concentrations. The version called the ADMS-URBAN model can handle line sources and includes a street canyon option. Both the ADMS-3 model and the ADMS-URBAN model are able to calculate pollutant levels for the averaging periods and percentiles set out in the UK National Air Quality Strategy. The new generation models have been shown to predict higher ground level concentrations than the Gaussian model ISC and R91, in certain cases.

The evaluation and validation of the ADMS model was published in papers (for example, Carruthers, et al 1998; Hana et al, 1999; CERC, 2001). The ADMS-3 model was compared with the USEPA AERMOD model and tested against measurement

data at monitoring sites in the Lower Trent Valley (Futter, 2000). It was also employed as a tool in research (for example, Colvile et al, 2002). The ADMS URBAN model was selected for air quality review and assessment stage 3 by local councils, such as Gateshead Council (Gateshead Council, No date), the London Borough of Croydon (2000), the London Borough of Barnet (1998), and the Borough of Bracknell Forest (Bracknell Forest Borough Council, No date). The ADMS-3 model was used in the review and assessment stage 3 in the district of Hertfordshire (Hertfordshire Council, 2001). This model was used to estimate SO_2 concentration for the Port of Dover (Dover District Council, No date).

(3) AERMOD

The AERMOD (American Meteorological Society/Environmental Protection Agency Regulation Model) is the US new generation air quality modelling system (DEFRA, 2000; UWE, 2002). It has been developed with the intention to replace the ISC model. It contains improved algorithms for convective and stable boundary layers, for computing vertical profiles of wind, turbulence and temperature, and for the treatment of all types of terrain. The AERMOD model can be used with UK meteorological and terrain data using a suite of programs developed by Trinity Consultants. The AERMOD model was used to assess PM_{10} from the process of road stone coating in the review and assessment stage three for Arun District Council (2000). The model was used to assess NO_2, SO_2, and PM_{10} from industrial sources in the Borough of Newport County (Newport County Borough Council, 2001). The South East Institute of Public Health (SEIPH) also employed this model and the ADMS –Urban model for air quality review and assessment in the London Borough of Wandsworth (Wandsworth Borough Council, No date).

(4) BREEZE ROADS

This is a USEPA modelling package, which includes the CAL3QHC, CAL3QHCR and CALINE4 models (DEFRA, 2000). In combination with an emission model it has versatile applications for calculating roadside concentrations in many complex road situations. The model can account for hourly, daily and seasonal variations in traffic flows and provides output for a range of averaging periods comparable with the air quality objectives. The BREEZE ROADS package was used for air quality review

and assessment at stage 3 in districts, such as Wokingham (Wokingham Unitary. 2002), West Berkshire (West Berkshire Council. 2001), Rugby Borough (Rugby Borough Council, 2001), Arun (Arun District Council, 2000) and Newport County Borough (Newport County Borough Council, 2001).

(5) CALINE model

The CALINE (CALifornia LINE Source Dispersion Model) model was developed by the California Department of Transportation and the US Federal Highway Agency (FHA) (DEFRA, 2000; Fisher, 2000c; UWE, 2002). The model is based on the Gaussian equation and employs a mixing zone concept to characterize pollutant dispersion over the roadway (CALTRANS, 2001). The CALINE4 model seems to achieve widest acceptability in the UK. The model can calculate the hourly average concentrations in specific meteorological conditions. Adjustments are necessary to deal with episodes of low wind speed and stable conditions which persist for several days. However it contains many features specific to roads, such as queues at traffic junctions, parking lots etc. The CALINE model was used in the UK, for example, in stage 2 of air quality review in the Borough of Bracknell Forest (Bracknell Forest Borough Council, No date), and for stage 3 review and assessment for NO_2 in the Mid Beds District Council (2000).

(6) Fluidyn-PANACHE model

The Fluidyn-PANACHE model is potentially a much more powerful model as it is relied on computational fluid dynamics, to solve the flow and dispersion around roads and industrial sources (DEFRA, 2000; Fisher, 2000c; UWE, 2002). It is capable of dealing with gaseous or particulate emissions. Specific features include modelling urban photochemistry ozone production, forest and vegetation effects (dry deposition and porosity). The model is able to simulate very low wind speeds, and wind flow patterns around uneven terrain and high building. Its graphical interface removes the complexity and hard work normally required to set up and run these kinds of models.

(7) Indic AirViro System

The Indic AirViro system is a modelling system and requires a UNIX work station rather than a PC. The system has in-built wind models, complex terrain handling, and

direct links to a dynamic emissions database which can handle almost unlimited numbers of point, area, and line sources, and grid layers (DEFRA, 2000, Fisher, 2000c; UWE, 2002). The model requires complex physical, geographical and meteorological information. The Indic AirViro system provides dispersion simulation at different scales with the option of five models: Street Canyon, Urban, Grid, match. and Heavy Gas. The dispersion results are overlaid on a map and can be imported/exported to standard GIS software. The system can be applied using a number of Gaussian model options and a street canyon option. However other dispersion models can be programmed into the system. The data input facilities, output and display options and a database for processing measurements from a network of air pollution monitors are included in the system. The database within the Indic AirViro system has been used to collect and access monitoring data, which was measured at the Enhanced Urban Network sites in UK city centres, such as Birmingham. The Indic AirViro model was used to review and assessment at stage three in local authorities, for example, in the Borough of Rotherham (Rotherham MBC, 2000), and the Borough of Charnwood (2000).

(8) ISC Model

The ISC (Industrial Source Complex) model is a USEPA multi-source Gaussian model and has been accepted for many industrial source modelling applications (DEFRA, 2000; Fisher, 2000c; UWE, 2002). Gravitational settling of particles can be accounted for by using a dry deposition algorithm; wet deposition and depletion due to rainfall can also be treated. The effects of buildings can be considered. The model has urban and rural dispersion coefficients, and the percentile concentration can be calculated using the PERCENT post-processor, if sequential meteorological data are used. This model has found widespread appeal especially to users in the UK. Apart from the long-term version of this model, ISCLT, in which annual averages can be calculated, there is also a short-term version ISCST in which hourly average levels can be calculated. The model can be used to calculate concentrations from point, small area and volume sources, but can lead to difficulties for wide area sources. It can handle up to 1,000 sources and 10,000 receptors. The ISC3 model was used in air quality review and assessment stage 3 in the Borough of Rugby (Rugby Borough Council, 2001).

(9) PAL model

PAL (Point, Area, and Line Source Model) is a USEPA model using the same Gaussian line source algorithms as the CALINE model, but it has special area source algorithms for treating edge effects more accurately, and is able to treat inclined line sources (DEFRA, 2000; UWE, 2002). This facility is useful for modelling car parks, small areas of cities and airports. Level terrain is assumed in the calculations, which can model up to 99 point, area and line sources, and 99 receptors.

(10) RTDM

The RTDM (Rough Terrain Diffusion Model) is a USEPA Gaussian model capable of predicting short term concentrations arising from point sources in complex terrain (DEFRA, 2000; UWE, 2002). It calculates 1-hour averages only, and there is no percentile post-processor. Building wake effects cannot be modelled, only rural dispersion coefficients are available. It requires on-site hourly measurements of turbulence intensity, vertical temperature difference, horizontal wind shear and wind profile exponents.

(11) TRAQS

The TRAQS (Traffic and Air Quality Simulation) is an integrated air quality assessment and management system (DEFRA, 2000). It includes a simulation model covering traffic flow, emission, dispersal and photochemistry, linking traffic demand directly to pollutant distribution. It involves GIS-based, full spatial analysis, on-line real-time data collection, inventory development tools, a selection of user specified air quality models, source optimization tools, traffic flow models and links to telemetric.

3.3.4 Use of screening models in an air quality review and assessment in the UK

The review in previous sections shows that the models were used for the academic or research purposes, and for regulatory use. Okamoto (1995) took the view that the models used for regulatory purposes should not be only convenient models for officers, but should also be the models, which have sufficient predictive performance for regulations. These kinds of models require higher levels of appropriateness and usefulness than research models do (Okamoto, 1995). In the UK, local authorities are

required by Part IV of the Environment Act 1995 to carry out a review and assessment of local air quality. In order to conduct an air quality review and assessment, local authorities are required to predict air pollutant concentrations in their local districts in future years with regard to UK National Air Quality Standards and Objectives in three stages. The screening and more detailed models for this regulatory purpose might be established at stage 2 and 3 of air quality review and assessment process (DEFRA, 2000).

From the study it is found that the screening models currently used in air quality review and assessment in the UK include the ADMS-SCREEN, CAR, DMRB, GRAM, and GSS models. The intermediate model is the AEOLIUS model. The advanced models are the AAQUIRE, ADMS-URBAN, ADMS-3, AERMOD, BREEZE ROADS, CALINE, Indic AirViro, and ISC models. This review is consistent with a previous study (Beattie, Longhurst, and Woodfield, 2001), which indicated that the most popular models were the DMRB model and the ADMS-URBAN model, and other models in use included the AEOLIUS, Indic AirViro, CALINE4, CAR, AAQUIRE, and USEPA models. It is found from the review that most local authorities commissioned environment consultants to conduct the review and assessment in their council areas. The same consultant always used the same models. However, it can be seen that the screening models, which have been used to estimate air quality from road transport in the UK are the CAR, DMRB, and GRAM models. The ADMS-SCREEN and GSS models have been used for screening predictions of pollutants from point sources.

3.4 Model selection

This research focuses on selecting a screening line source model from urban air quality models developed or used in the UK. The screening model represents a preliminary approach based largely on national average statistics (Highways Agency, 1999), and designed to simplify a source's emissions and provide conservative pollutant concentration impact estimates (Canter et al, 2000). Thus they are suitable for an initial stage of the development of a new urban air model for assessing the impact of road transport on air quality in Bangkok. The screening line source models, which are developed or used in the UK as found in the previous section, are the CAR,

DMRB, and GRAM models. Recently, a model named 'LEZ model' has been used to propose the road reduction targets in the authority area of Westminster City Council (Cloke, no date). The LEZ model is the National Society for Clean Air and Environmental Protection (NSCA) Low Emission Zones Toolkit designed to provide an assessment of changes in traffic on emission and concentration in a zone in question. Thus, the LEZ model was also included for this research. All models are computer-based programs run on a PC. The methodology for selecting the models was as follows.

3.4.1 Methodology

For screening the required air quality models, criteria were formulated based on the application, the pollutants, the future year of prediction, the data available in Bangkok, and the model assessment. These are needed for a model to be used to develop policy on improving air quality. The detail of criteria was as the following:

1. Designed for predicting the impact of road transport on urban air quality.
2. Can predict all of the following pollutants: CO, NO_2, benzene, and PM_{10} in an urban area, because CO, NO_2, and PM_{10} are currently the most significant pollutants in London and Bangkok. Benzene is also of interest because it is being included in Thailand's Air Quality Standards (Rungruksathum, 2000). On a UK national basis, motor vehicles accounted for about 60% of total benzene emissions in 1997 (DETR, 2000a). In London, this ratio rises up to 83% in the 1995 London emission inventory (LRC, 1997).
3. Can predict urban air quality in the future years until 2025, in order that the model can evaluate the impacts of road transport and the effectiveness of mitigation measures on urban air quality over long term periods.
4. Input data needed for models are available in Bangkok.
5. The model has been evaluated with data sets in air quality assessment applications.

The description of the models was studied and the models that met all requirements in the criteria were selected for further study and the testing of their performance.

3.4.2 Results and discussion

3.4.2.1 Description of the models

CAR (Calculation of Air Pollution from Road Traffic) model

The CAR model studied by this research was version 1.0, released in 1993. The model works in MS DOS. It predicts the CO, NO_x/NO_2, and daily benzene concentrations in term of daily average concentration, 98-percentile of 1-hour mean concentrations, the 98-percentile of 8-hour mean concentrations, and 98-percentile of 24-hour mean concentrations. It should be possible to convert these concentrations into a form, which was approximately equivalent to the form in which the UK air quality objectives are expressed. If one wanted to calculate the concentrations in future years, the input data, e.g. traffic volume, urban background concentration, emission factors, of the future year would need to be known. Types of input and output data are shown in Tables 3.1 and 3.2.

Table 3.1 CAR input data

Term	Unit	Condition
Street name	-	-
City diameter	km	Maximum 50 km
Fraction of trucks and buses	-	Between 0.0 – 1.0
Number of vehicle per day	vehicle	Between 100 – 150,000
Distance to the road axis	m	Between 5 – 30 m
Road type	-	1,2,3a, or 4
Speed type	-	a, b, c, or d
Tree factor	-	1.00, 1.25, or 1.50
Emission factor	μg/m/s	Emission factors of cars and trucks/buses at average speed of 13, 22, 44, 100 km/h
Fraction of directly emitted NO_2	-	-
City/regional background concentration	μg /m^3	-
Annual mean wind speed at 10 m height.	m/s	-

Source: CAR (1993)

Note:

Road type: 1 = road in open terrain, a few building or trees; 2 = base type, all roads different from type 1, 3a, 3b or 4; 3a = broad street canyon (< 3hb); 3b = moderately narrow street canyon (>0.5 hb, and < 1.5 hb);
4 = building at only one side of the road

Speed type: Va = highway; Vb=road with maximum speed 70 km/h; Vc = regular city traffic; Vd = stagnating traffic

Tree factor: 1.00 = very few or no trees on either side of the street; 1.25 = trees on one side of the street
1.50 = trees on both sides of the street. The tree tops touch each other

Table 3.2 CAR output data

Pollutant	Unit	Term
Benzene	μg/m^3	Daily mean, 98-percentiles: 1-hour mean, 8-hour mean, and 24-hour mean
CO	μg/m^3	Daily mean 98-percentiles: 1-hour mean, 8-hour mean, and 24-hour mean
NO_2	μg/m^3	Daily mean 98-percentiles: 1-hour mean, 8-hour mean, and 24-hour mean

Source: CAR (1993)

DMRB – Design Manual for Roads & Bridges

The DMRB model works in Microsoft Excel. Stanger Science and Environment had developed two versions of the DMRB models: the DMRBV1 and DMRBV2 models (Stanger Science and Environment, 1999, 2000). They were designed, following the procedures described in LAQM.TG4 (00), to predict the impacts of road traffic up to 20 links on one receptor at a time for one given year from 1996 to 2025. The first version: DMRBV1 can estimate the CO, benzene (C_6H_6), NO_x, and gravimetric PM_{10}, in terms of the roadside annual mean concentration and the total annual mean concentration (roadside + background concentrations). The background annual mean concentration is part of the input data. Urban background concentrations have normally to be supplied to the model from locally available measurements. This version included a factor, which converts the total annual mean NO_x to annual mean NO_2.

The later version of the DMRB mode is the DMRBV2. It had been released to public since 28th March 2000. The general conditions on input data are the same as the DMRBV1 model. The new model gives more results in addition to the annual mean NO_2. For comparison with the Air Quality Objectives, in this version, the maximum 8-hour mean CO, the maximum running annual mean benzene, the 90th Percentile of daily mean PM_{10} are supplied as output. The calculated results are the same as the values in the DMRBV1 model, except the value of benzene in the DBRMV2 model is lower than that in the DMRBV1 model. For example, the DMRBV1 model estimates the annual mean benzene of 11.6 $\mu g/m^3$ at the Marylebone Road monitoring site in 1998, whereas the DMRBV2 model estimates the lower level of 9.6 $\mu g/m^3$. The DMRBV2 model was used in this thesis. Terms in the input and output data are shows in Tables 3.3 and 3.4.

Table 3.3 DMRBV2 input data

Term	Unit
Receptor name	-
Year to be model	-
Descriptor of link, up to 20 links	-
Distance from receptor from centre road	m
Distance from receptor from kerbside	m
Annual average vehicle flow	veh/h
Percentage of HDV in the vehicle fleet	%
Average speed	km/h
Background concentration of benzene, CO, NO_x, and PM_{10} for the year to be modeled	$\mu g/m^3$ (benzene, NO_x, PM_{10}) mg/m^3 (CO)

Source: Stanger Science and Environment (2000)

Table 3.4 DMRBV2 output data

Pollutant	Unit	Term
Benzene	$\mu g/m^3$	Roadside annual mean, Total annual mean, Maximum running annual mean*
CO	mg/m^3	Roadside annual mean, Total annual mean, Maximum 8-hour mean*
NO_x	$\mu g/m^3$	Roadside annual mean, Total annual mean
NO_2	$\mu g/m^3$	Annual mean*
PM_{10}	$\mu g/m^3$	Roadside annual mean, Total annual mean, 90^{th} Percentile of daily mean*

Source: Stanger Science and Environment (2000)
Note: * for comparison with the UK Air Quality Objectives

GRAM – University of Greenwich's Review of Air Quality Method

GRAM is a screening model, which works in Microsoft DOS. It can predict the impacts of road traffic from one link at receptors at up to 100 sites from road at one time, for one given year between 1996 and 2025. The model can estimate the concentration of CO, NO_x, NO_2, benzene, and gravimetric PM_{10} in term of roadside. background, and total mean concentration. The model incorporates the DMRB emission factors, and the CALINE4 and R91 dispersion curves. It yields the concentration of those pollutants under the assumption of worst case meteorological conditions and presents the results in the form needed by the UK National Air Quality Strategy Target (Fisher, 1998a, 1998b, 1999a). Terms in the input and output data of the GRAM model are shown in Tables 3.5 and 3.6 respectively.

Table 3.5 GRAM input data

Term	Unit
Vehicle speed	km/h
Traffic flow	veh/day
Year to be modelled	-
Predicted traffic growth	%
Fraction of HDV	-
Diameter of urban area	km
Emission density of NO_x, CO, VOCs, and PM_{10}	$t/km^2/y$
Regional PM_{10} concentration	$\mu g/m^3$
Distance from receptor to road centre line, up to 100 values	metre

Source: Fisher (1998b)

Table 3.6 GRAM output data

Pollutant	Unit	Term
Benzene	ppb	Roadside annual mean, Background annual mean, Total annual mean
CO	ppm	Roadside maximum 8-hour mean, Background 8-hour mean, Total maximum 8-hour mean*
NO_x	ppb	Roadside 18th highest hourly mean, Background hourly mean, Total 18th highest hourly mean, Roadside annual mean, Background annual mean, Total annual mean
NO_2	ppb	18th hourly mean*, Annual mean*
PM_{10}	$\mu g/m^3$	Roadside annual mean, Background annual mean, Total annual mean*, Exceedences of daily mean*

Source: Fisher (1998b)
Note: * for comparison with the UK Air Quality Objectives

LEZ – Low Emission Zones Model

LEZ model is developed by Transport and Travel Research and the University of West of England for the National Society for Clean Air and Environmental Protection (Transport & Travel Research and the University of West of England, 2000). The version described in this thesis is version 1.3, released on 10th March 2000. The model working in Microsoft Excel estimates changes in fuel consumption, changes in traffic emissions of CO_2, CO, HC, NO_x, SO_x, and PM_{10}, and changes in concentrations of CO, NO_x, and PM_{10}, from the current traffic to the scenario. The model uses a single box as a dispersion model under the worst case conditions (NSCA, 2000). The prediction covers the road contribution only. The model gives results as a short-term mean e.g. 24 hour. The future year concentrations cannot be estimated. The model needs, as input data, the vehicle type in term of EURO standard for estimating the concentrations in the area zone of interest. The model suggests that

this data (in the UK) can be obtained from the DVLA for post code areas. The input and output data are shown in Tables 3.7 and 3.8 respectively.

Table 3.7 LEZ input data

Term	Unit
Characteristics	
Population in zone (option)	pop
Households in zone (option)	household
Area of zone	km^2
Population density (option)	pop/km^2
Households density (option)	hh/km^2
Length of road network (option)	km
Current vehicles	
Vehicle type (car, van <3.5t, Bus, HGV) in fuel type split (petrol, diesel)	%
Vehicle type (car, van <3.5t, Bus, HGV) in age split (pre EURO 1/pre 1993, EURO 1/1993-1996, EURO 2/ post 1996)	%
LEZ Scenario	
Vehicle type (car, van <3.5t, Bus, HGV) in age split (pre EURO 1, EURO 1, EURO 2, EURO 3, EURO 4)	%
Traffic data	
Vehicle speed of car, van <3.5t, Bus, and HGV, in current time and scenario	km/h
Vehicle-km travelled of car, van <3.5t, Bus, and HGV, in current time and scenario	1000 v-km

Source: Transport & Travel Research and the University of West of England (2000)

Table 3.8 LEZ output data

Term	Unit
Exhaust emissions	
Total fuel consumption and emissions of CO_2, CO, HC, NO_x, SO_x, and PM_{10} of each vehicle type in current mode and LEZ scenario mode	kg (fuel) kg (emissions)
Changes in total fuel consumption and emissions by vehicle type and by mode	kg (fuel) kg (emissions)
Emissions of each pollutant per vehicle-km by vehicle type and by mode	g/v-km
Emissions of each pollutant per head of population by vehicle type and by mode	g
Emissions of each pollutant per household by vehicle type and by mode	g
Emissions of each pollutants per km of road network by vehicle type and by mode	kg/km
Change in concentrations	
Q – value for change in emissions of CO, NO_x, and PM_{10} by vehicle type	$\mu g/m^2/s$
Change in concentrations under stable winter condition of CO, NO_x, and PM_{10} by vehicle type	ppm (CO) ppb (NO_x) $\mu g/m^3$ (PM_{10})

Source: Transport & Travel Research and the University of West of England (2000)

3.4.2.2 Assessment of models against criteria

The CAR model was designed for the calculation of air pollution from road traffic. The model has been evaluated against the measurements (Eerens, Sliggers, and Hout, 1993). It can predict the pollutants of CO, NO_2, and benzene. However PM_{10}, which is one of the target pollutants, is not included. It can give a prediction in future years if the input data for future years are known. It needs input data two of which are not

available in Bangkok. Traffic flows on some major roads in Bangkok exceed the conditions of the CAR model, such as the daily traffic flow on the Wipawadeerungsit Road, approximately 194,000 vehicles per day in 1998 (OCMLT, 1999). Moreover, the model needs some post-calculation for assessing concentrations in the form required by air quality standards in Thailand. Thus, it can be concluded that the CAR model does not conveniently meet the second and fourth criteria. In principle, it may also be possible to adjust the input so as to generate the concentration from a road carrying heavier traffic than the limiting condition of 150,000 vehicles per day. Moreover although PM_{10} is not included, it should be possible to obtain estimates by suitably scaling other concentrations. However, the CAR model would not be the model of the first choice. In addition, a complete description of the formulae used in the model is not available, nor is there a listing of the computer code. For these reasons, this is not the preferred model for modifying to an air quality model for Bangkok.

The DMRB model is a model for predicting the impact of road transport. The pollutants predicted by this model are of NO_2, CO, benzene, and PM_{10}. The model gives the prediction until 2025. All input data required are available in Bangkok. The model has been assessed with data sets to air quality assessment application (Fisher, Moorcroft, and Vawda, 1999; Mann, Moorcroft, and Laxen, 2001). Thus, the model fits all criteria. The GRAM model was designed for predicting the impact of road transport on urban air quality. The model has been assessed with data sets for air quality assessment application (Fisher and Sokhi, 2000). It can predict the concentrations of NO_2, CO, benzene, and PM_{10}. The prediction covers the period of 1996 – 2025. Moreover, the input data required are available in Bangkok. Thus, this model also meets all criteria.

The LEZ model estimates road contribution only. Thus it cannot be used for predicting urban air quality or total level of pollutants, which need the urban background concentration incorporated into the calculation. The model gives the results as the NO_x only. NO_2 and benzene is not included. It cannot predict the concentration of air pollutants in a future year. It requires the vehicle type in term of the EURO standard, which is not available in Bangkok. The data available in

Thailand are the vehicle type in terms of fuel type. It has been used to test low emission zone scenarios in the district of Westminster Council. in order to assess the practicality of controlling vehicles (Cloke, No date). The work assessed the changes in emissions and concentrations, but did not include an evaluation against air quality measurements. Thus, it can be concluded that the LEZ model does not easily meet all of the criteria.

The models' descriptions against each criterion are shown in Table 3.9. It was found that the DMRB and GRAM models met all criteria in a convenient manner. Hence they were chosen for further study in which their performance was evaluated.

Table 3.9 Model description against the criteria

Model	Criterion				
	1	2	3	4	5
CAR	√	x	√	x	√
DMRB	√	√	√	√	√
GRAM	√	√	√	√	√
LEZ	x	x	x	x	x

Note: √ = meets requirement, x = does not meet requirement

However, there is a difference between the DMRB and GRAM models regarding estimates of urban background concentration. The DMRB model needs the measurement of the urban background concentration as the input data. It predicts the annual mean NO_2 and maximum 8-hour mean CO. from the measurement of the background concentrations of the annual mean NO_x and the annual mean CO. respectively. The model uses the input data of the annual mean C_6H_6 and the annual mean PM_{10} from measurements at urban background stations directly. In contrast the GRAM model needs the emission density of NO_x, CO, VOCs, and PM_{10} in the study area, and the regional PM_{10} concentration around the study area as the input data. These data are then used to calculate the background concentration. For both the DMRB and GRAM models, all the formulae used in the calculations are known. In the case of the GRAM model these could be checked against primary references.

3.5 Model evaluation

The DMRB and GRAM models were tested for their performance in London and Bangkok, so as to select a model that has a potential to become an air quality model for Bangkok. To evaluate their performance a methodology was undertaken as in the following section.

3.5.1 Methodology

The performance of the models was evaluated based on a physical and statistical basis. The physical basis was conducted by comparing the values and plots of the predictions against measurements. National standards were included in the comparison so as to indicate the priority of the pollutants. The root mean square difference (RMSD) was chosen as the statistical measure. The root mean square difference is a summary statistic to show the error of the calculated, or estimated values from the observed, or the measured values. This statistic was used as the tool to indicate which model was performing well. This is known as model validation. It is traditional to validate predictions using a root mean square score (Environment Canada, 2001). This is a common method used by many investigators to quantify the 'goodness-of-fit' of model predictions and observations (Ghaffari, Cook, and Lee, 2001). This method was recommended by DEFRA for estimating a model's uncertainty (DEFRA, 2000).

The root mean square difference showed the average of the difference between the estimates of a model at all target receptors against the measurements of a pollutant. The model showing lower values of the root mean square difference than another model performed better than the other models. The formula of the root mean square difference is:

$$r = \sqrt{(1/n)\sum_{i}^{n} (C_i - O_i)^2}$$

where r = root mean square difference

C_i = calculated or estimated value

O_i = observed or measurement value

n = number of observed or calculated values.

The root mean square difference has been utilized in comparison of calculated and observed data in several fields by researchers (for example, Ghaffari, Cook, and Lee, 2001; Henmi, No date; Chu, 2000; Luckey and Becker, 1999; Tracy and Cialone, 1996). There are other measures, which have been used to compare predictions with observations, for example, the mean difference (MD) (Henmi, No date; Luckey and Becker, 1999), the mean absolute difference (AD) (Henmi, No date; Luckey and Becker, 1999), the correlation coefficient (CC) (Micallef and Colls, 1999; Henmi, No date; Chu, 2000; Karippinen et al, 2000), and the index of agreement (ID) (Cai and Steyn, 2000; Karippinen et al, 2000), etc. The MD, at a non-zero MD, indicates bias (Henmi, No date). The AD taking small values means good agreement (Henmi, No date). The CC indicates the correlation between the two model data sets (Henmi, no date, Chu, 2000). The ID varies from 0.0 (theoretical minimum) to 1.0 (perfect agreement) (Cai and Steyn, 2000; Karippinen et al, 2000). Sometimes the bias $\overline{C}_i - \overline{O}_i$ is used as a measure of the difference, but sometimes the bias can be nearly zero, even when there are considerable differences between calculated and observed values at target receptors. The root mean square was chosen for this research.

3.5.2 Input data and measurements

The automatic air quality monitoring stations in London and Bangkok were assigned as the receptor sites for evaluating the DMRB and GRAM models. In this research, the 1998 measured data from the eight urban air quality monitoring stations in London, which fall into three site types: kerbside, roadside, and urban background, were chosen. The kerbside station was the Marylebone kerbside station. The roadside stations were the Sutton roadside, the Haringey roadside, the Camden roadside and the A3 roadside stations. The urban background stations were the Bexley, Brent, and North Kensington monitoring sites. The pairs of urban background-roadside/kerbside stations needed as DMRB's input data are Bexley-Sutton, Bexley-A3, Brent-Haringey, Brent-Camden, and North Kensington-Marylebone. Input data for the predictions of the DMRB and GRAM models in London are shown in Table 3.10.

Air quality monitoring stations at four roadside sites and four urban background or general sites, operated by the Pollution Control Department were chosen for the predictions of the two models in Bangkok. The roadside stations were the

Chulalongkorn, Dindaeng, Ladphrao, and Thonburi Electricity stations. The urban backgrounds, or general stations, were the Nonsi. Ramkhumhaeng, Klong Jun and Singharach stations. The pairs of urban background-roadside station needed as DMRB's input data are Nonsi-Chulalongkorn, Ramkhumhaeng-Dindaeng, Klong Jun-Ladphrao and Singharach-Thonburi Electricity. All input data are shown in Table 3.11.

The predicted values were compared with the year 1998 measurements at those air monitoring stations. The required measured values in London were collected from the DETR data base available on the DETR website (DETR, 2000c). The measurements in Bangkok were collected from Department of Pollution Control (PCD, 1999b) as hourly data, which were then processed to the required form. The required measured values were the annual mean NO_2, the maximum 8-hour mean CO, the annual mean C_6H_6, and the annual mean PM_{10}. In the case of C_6H_6, this was measured in London at only three stations: Marylebone (a roadside station), London Eltham (a suburban station) and London UCL (a roadside station). Thus London Eltham was taken to be the background station for the estimates of C_6H_6 at all stations in the DMRB model. The results of C_6H_6 for Bangkok are not presented in the chapter as there are no measurements of C_6H_6 concentration in Bangkok.

Table 3.10 Input data for London

Factor	Sutton	Haringey	Camden	A3	Maryleborne	Bexley	Brent	N.Kensington
Station type	R	R	R	R	K	B	B	B
Vehicle speed (km/h)	25	25	20	40	25	-	-	-
Vehicle flow (vehicle/day)	20000	17000	45100	104000	71000	-	-	-
Year to be modelled	1998	1998	1998	1998	1998	1998	1998	1998
Traffic growth (%/y)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
HDV fraction	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Diameter urban area (km)	40	40	40	40	40	40	40	40
NO_x emission density ($t/km^2/y$)	60	60	60	60	60	60	60	60
CO emission density ($t/km^2/y$)	200	200	200	200	200	200	200	200
VOC emission density ($t/km^2/y$)	60	60	60	60	60	60	60	60
PM_{10} emission density ($t/km^2/y$)	4	4	4	4	4	4	4	4
Regional background PM_{10} ($\mu g/m^3$)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Background level of annual mean NO_x ($\mu g/m^3$)	69.3	60.8	60.8	69.3	79.4	69.3	60.8	79.4
Background level of annual mean CO (mg/m^3)	0.5	0.4	0.4	0.5	0.5	0.5	0.4	0.5
Background level of annual mean C_6H_6 ($\mu g/m^3$)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Background level of annaul mean PM_{10} ($\mu g/m^3$)	19.0	18.0	18.0	19.0	20.0	19.0	18.0	20.0
Distance from road centre line (m)	9.5	13.0	6.0	12.5	8.0	-	-	-
Distance from kerbside (m)	3.5	3.0	3.0	3.0	3.0	-	-	-
Distance from centre of London (km)	20.0	10.0	5.0	15.0	5.0	22.5	12.0	8.0

Source: DETR (1998a); Fisher (2000b)

Note: R = Roadise station, K = Kerbside station, B = Background station

Table 3.11 Input data for Bangkok

Factor	Chulalongkorn	Dindaeng	Ladphrao	Thonburi Electricity	Nonsi	Ramkhumhaeng	Klong Jun	Singharach
Station type	R	R	R	R	B	B	B	B
Vehicle speed (km/h)	11	13	20	27	-	-	-	-
Vehicle flow (vehicle/day)	67000	170000	110000	135000	-	-	-	-
Year to be modelled	1998	1998	1998	1998	1998	1998	1998	1998
Traffic growth (%/y)	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
HDV fraction	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Diameter urban area (km)	40	40	40	40	40	40	40	40
NO_x emission density ($t/km^2/y$)	120	120	120	120	120	120	120	120
CO emission density ($t/km^2/y$)	190	190	190	190	190	190	190	190
VOC emission density ($t/km^2/y$)	-	-	-	-	-	-	-	-
PM_{10} emission density ($t/km^2/y$)	10	10	10	10	10	10	10	10
Regional background PM_{10} ($\mu g/m^3$)	54.0	54.0	54.0	54.0	54.0	54.0	54.0	54.0
Background level of annual mean NO_x ($\mu g/m^3$)	88.2	52.7	65.4	47.2	88.2	52.7	65.4	47.2
Background level of annual mean CO (mg/m^3)	1.1	0.9	0.9	1.2	1.1	0.9	0.9	1.2
Background level of annual mean C_6H_6 ($\mu g/m^3$)	-	-	-	-	-	-	-	-
Background level of annaul mean PM_{10} ($\mu g/m^3$)	64.6	59.7	58.7	69.1	64.6	59.7	58.7	69.1
Distance from road centre line (m)	20.0	15.0	15.0	20.0	100.0	100.0	100.0	100.0
Distance from kerbside (m)	5.0	5.0	5.0	10.0	90.0	90.0	90.0	90.0
Distance from centre of Bangkok (km)	2.0	3.2	8.5	5.8	4.0	9.5	13.0	11.2

Source: BMA (1999b); MOTC (1999); OCMLT (1999); PCD (2000a, 2000b)

Note: R = Roadise station, B = Background station

3.5.3 Results and discussion

Table 3.12 and Figures 3.1-3.4 show the comparison of the DMRB and GRAM models against the measurements at air quality monitoring sites in London in 1998. The root mean square difference (RMSD) of the two models evaluated at the roadside site and urban background site is shown in Table 3.13.

Table 3.12 Comparison of the DMRB and GRAM models against the measurements at air quality monitoring sites in London in 1998

Model	Sutton	Haringey	Camden	A3	Maryleb.	Bexley	Brent	N.Kensin
Annual mean NO_2 ($\mu g/m^3$)								
UK Objective	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Measurement	41.9	53.3	62.9	57.2	91.4	40.0	34.3	45.7
DMRB	70.4	63.9	107.3	135.6	128.1	34.5	31.3	38.1
GRAM	40.4	39.1	53.7	53.1	52.4	33.5	33.5	33.5
Maximum 8-hour mean CO (mg/m^3)								
UK Objective	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6
Measurement	4.6	nd	nd	8.8	7.3	3.9	4.9	3.5
DMRB	7.1	5.7	10.3	12.8	13.5	4.6	3.5	4.6
GRAM	7.1	6.9	9.0	9.3	9.8	6.1	6.1	6.1
Annual mean C_6H_6 ($\mu g/m^3$)								
UK Objective	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3
Measurement	nd	nd	nd	nd	12.8	nd	nd	nd
DMRB	4.6	4.3	7.9	9.7	9.6	nd	nd	nd
GRAM	3.2	3.0	4.9	5.4	5.7	2.3	2.3	2.3
Annual mean PM_{10} ($\mu g/m^3$)								
UK Objective	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Measurement	21.0	22.0	25.0	24.0	32.0	19.0	18.0	20.0
DMRB	27.4	24.9	39.9	51.4	49.6	19.0	18.0	20.0
GRAM	24.5	24.1	28.2	29.9	29.8	22.6	22.6	22.6

Table 3.13 Root mean square difference (RMSD) of the DMRB and GRAM models at the roadside/kerbside sites and urban background sites in London in 1998

Factor	Roadside/kerbside station		Urban background station	
	DMRB	GRAM	DMRB	GRAM
Annual mean NO_2 ($\mu g/m^3$)	45.6	19.1	5.7	8.0
Maximum 8-hour mean CO (mg/m^3)	4.5	2.1	0.9	2.1
Annual mean C_6H_6 ($\mu g/m^3$)	3.2	7.1	0.0	0.4
Annual mean PM_{10} ($\mu g/m^3$)	16.3	3.6	0.0	3.7

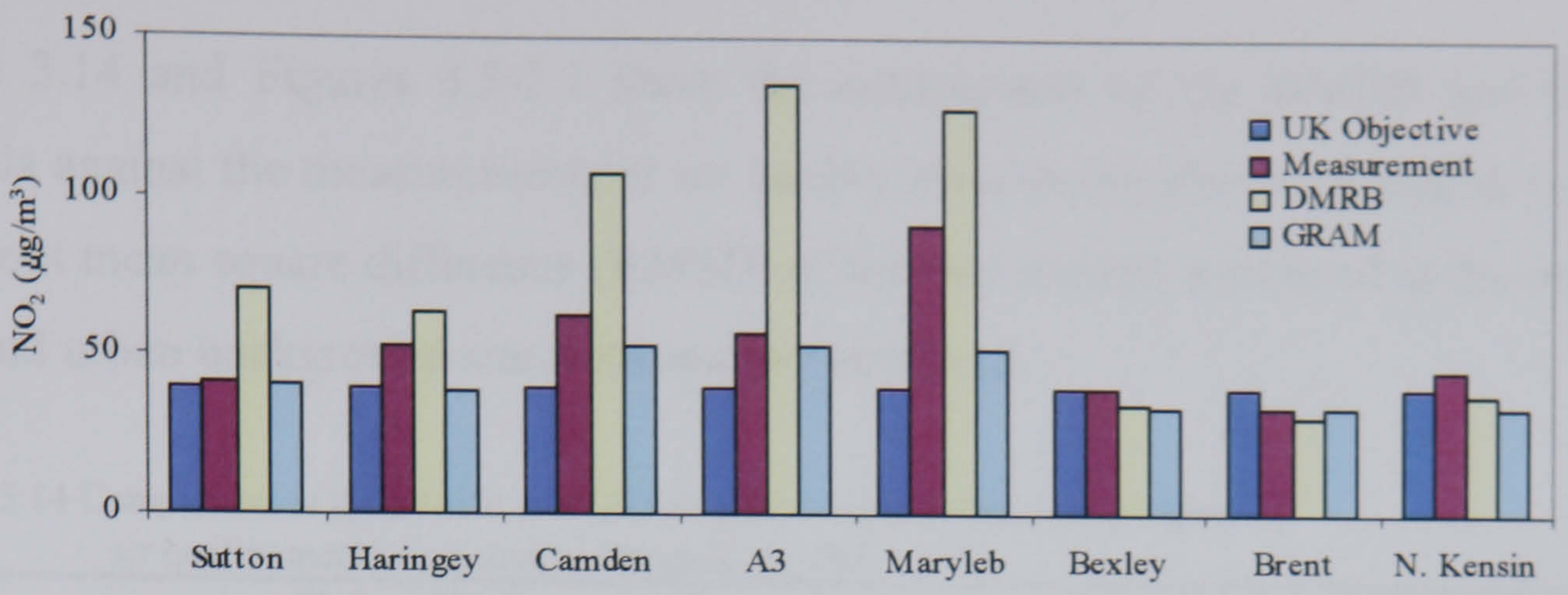


Figure 3.1 Comparison of prediction, measurement and objective of the annual mean NO_2 in London

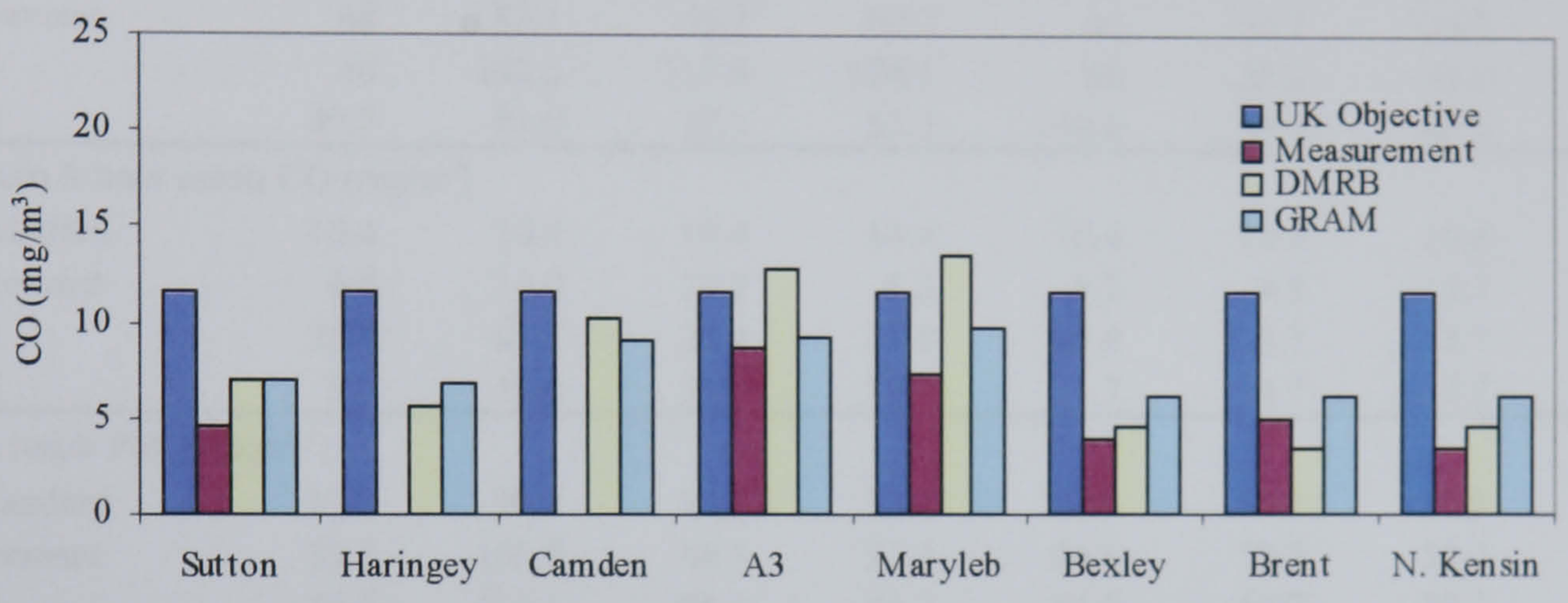


Figure 3.2 Comparison of prediction, measurement and objective of the max 8-h mean CO in London

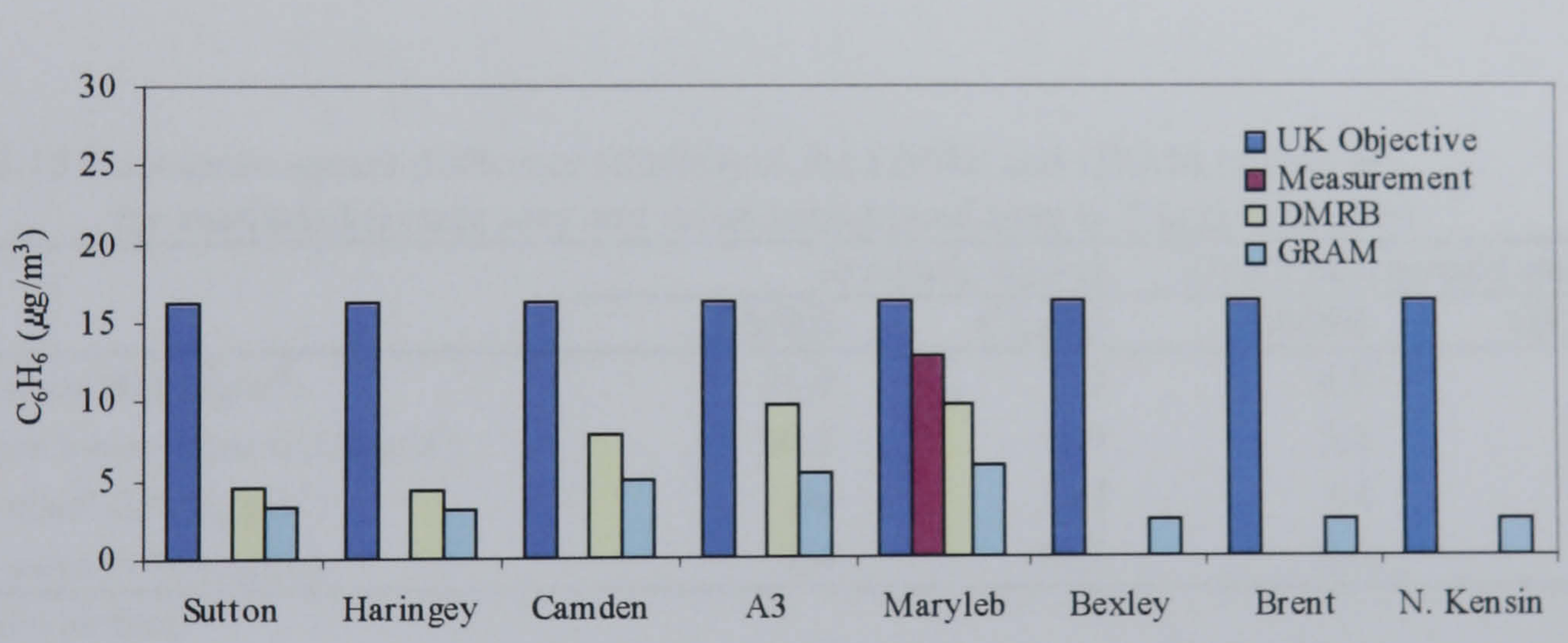


Figure 3.3 Comparison of prediction, measurement and objective of the annual mean C_6H_6 in London

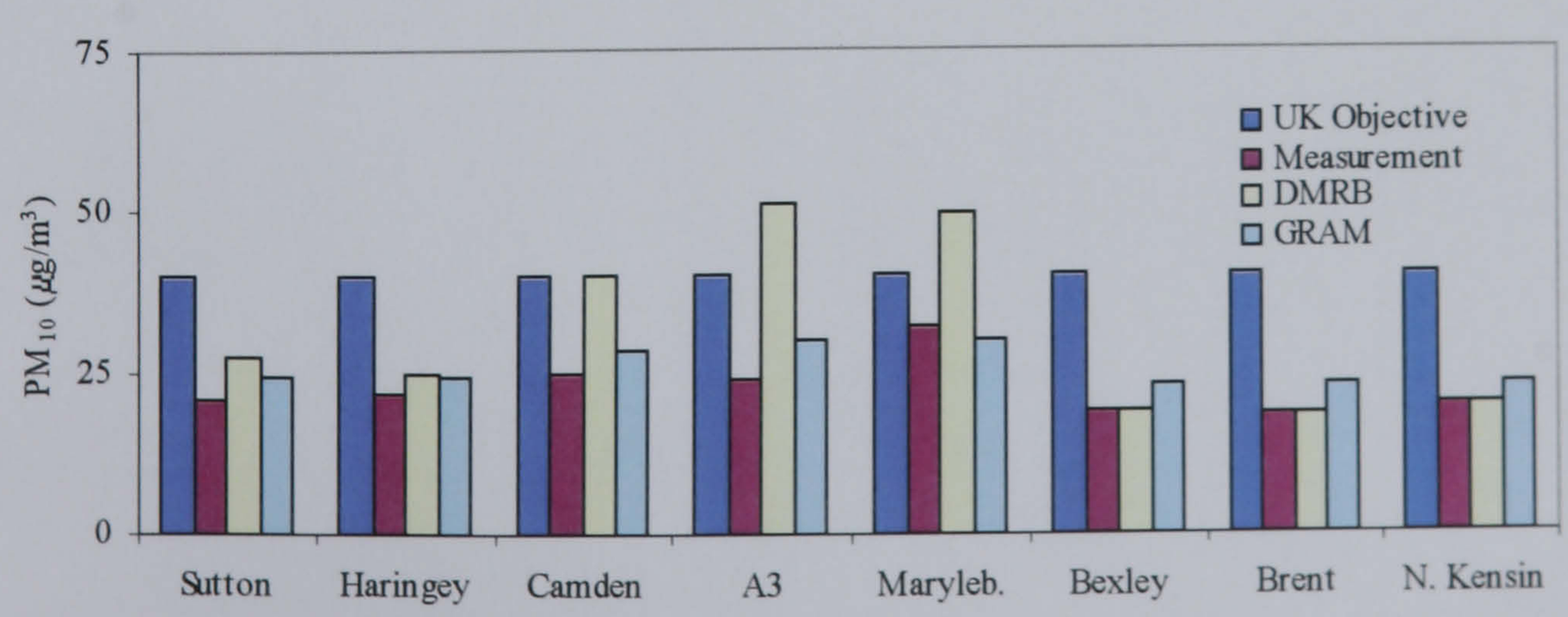


Figure 3.4 Comparison of prediction, measurement and objective of the annual mean PM_{10} in London

Table 3.14 and Figures 3.5-3.7 show the comparison of the DMRB and GRAM models against the measurements at air quality monitoring sites in Bangkok in 1998. The root mean square difference (RMSD) of the two models evaluated at the roadside site and urban background site is shown in Table 3.15.

Table 3.14 Comparison of the DMRB and GRAM models against the measurements at air quality monitoring sites in Bangkok in 1998

Model	Chula.	Dindaeng	Ladphrao	Thonburi	Nonsi	Ramkhum	Klong Jun	Singha
Annual mean NO_2 ($\mu g/m^3$)								
WHO guideline	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Measurement	nd	83.1	45.9	60.2	nd	34.7	36.9	28.4
DMRB	nd	162.5	117.6	124.1	nd	28.2	33.1	26.0
GRAM	49.7	81.0	57.1	52.3	40.6	40.6	40.6	40.6
Maximum 8-hour mean CO (mg/m^3)								
Thai Standard	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4
Measurement	6.8	13.0	20.9	6.3	5.2	4.5	5.3	4.9
DMRB	23.4	43.7	25.4	25.8	10.8	8.7	8.7	12.3
GRAM	9.7	16.9	11.0	10.3	4.7	4.7	4.7	4.7
Annual mean PM_{10} ($\mu g/m^3$)								
Thai Standard	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Measurement	85.3	100.8	80.3	91.4	64.6	59.7	58.7	69.1
DMRB	84.6	114.1	86.1	93.7	64.6	59.7	58.7	69.1
GRAM	74.2	93.0	75.8	75.4	69.7	69.7	69.7	69.7

Note: nd = no data

Table 3.15 Root mean square difference (RMSD) of the DMRB and GRAM models at the roadside/kerbside sites and urban background sites in Bangkok in 1998

Factor	Roadside station		Urban background station	
	DMRB	GRAM	DMRB	GRAM
Annual mean NO_2 ($\mu g/m^3$)	71.9	8.0	4.6	8.1
Maximum 8-hour mean CO (mg/m^3)	20.1	5.9	5.4	2.1
Annual mean C_6H_6 ($\mu g/m^3$)	nd	nd	nd	nd
Annual mean PM_{10} ($\mu g/m^3$)	7.4	10.7	0.0	7.9

Note: nd = no data

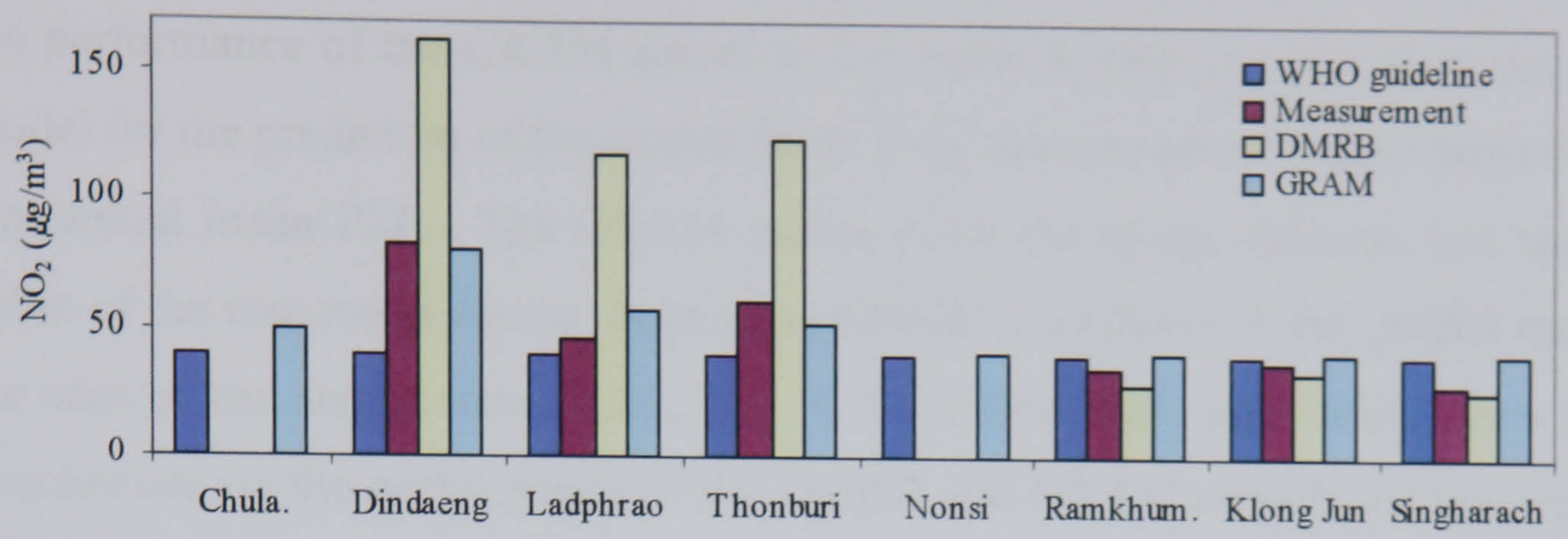


Figure 3.5 Comparison of prediction, measurement and objective of the annual mean NO_2 in Bangkok

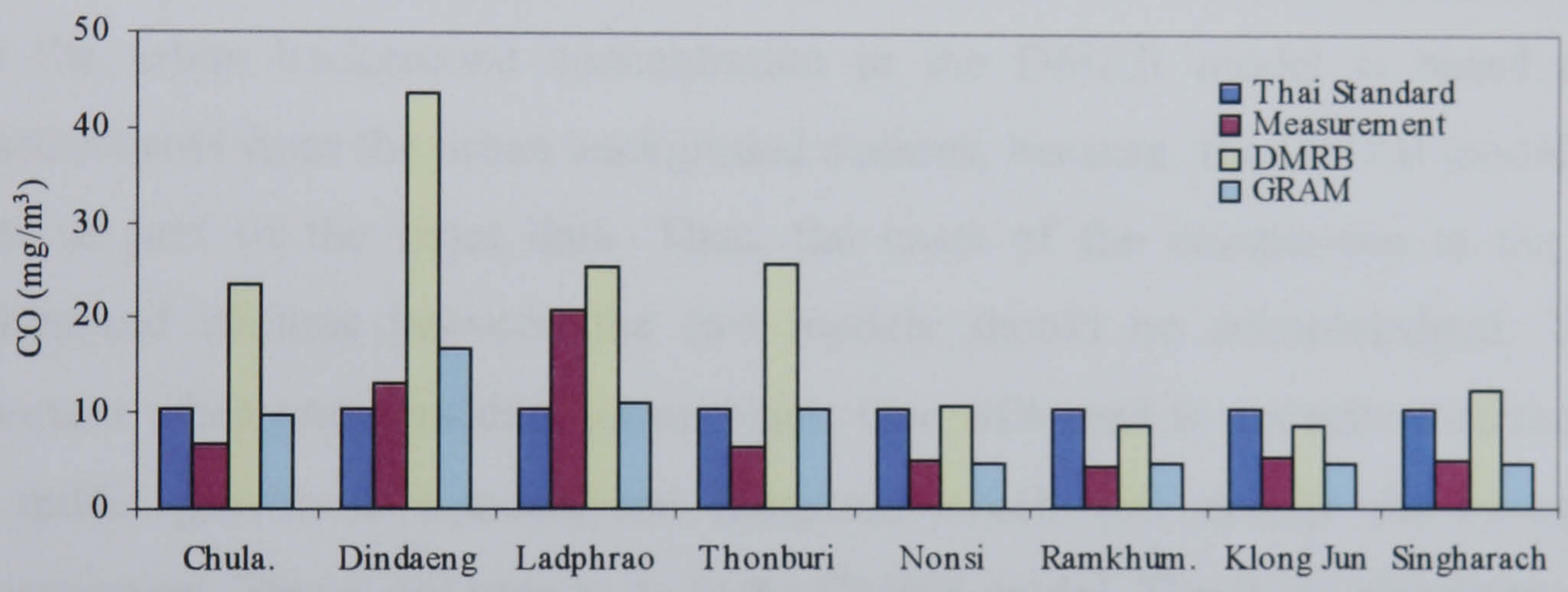


Figure 3.6 Comparison of prediction, measurement and objective of the max 8-h mean CO in Bangkok

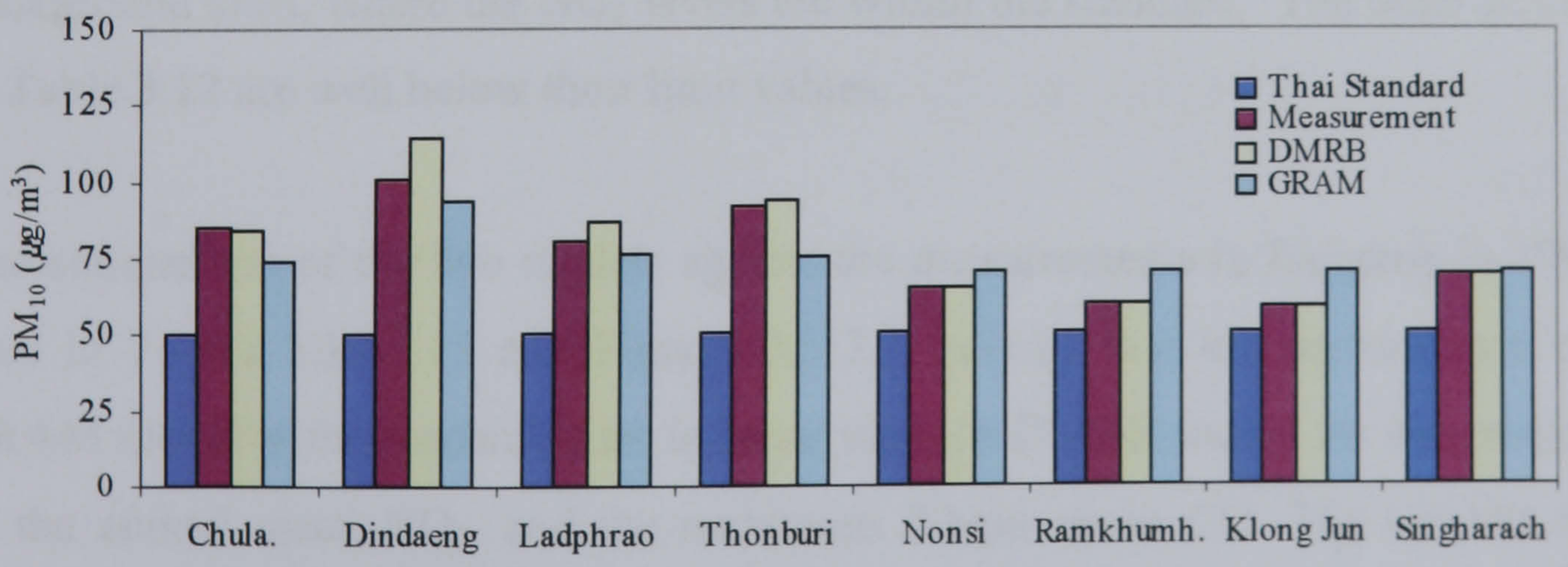


Figure 3.7 Comparison of prediction, measurement and objective of the annual mean PM_{10} in Bangkok

From the comparison of the DMRB model, the GRAM model, and the measurements in London, as shown in Tables 3.12-3.13 and Figures 3.1-3.4, it can be concluded that the performance of the GRAM model at the roadside sites is better than the DMRB model for the prediction of the annual mean NO_2, the maximum 8-hour mean CO, and the annual mean PM_{10}. The GRAM model gives the closer estimate and the lower value of the root mean square difference (RMSD) than those of the DMRB model. In the case of the annual mean C_6H_6, due to the limited data, one cannot draw general conclusions on the performance of the DMRB and GRAM models for the prediction of this factor. One can conclude that the DMRB model is performing better than the GRAM model at the Marylebone station for the predictions of the annual mean C_6H_6. Even though the results show that the performance of the DMRB model at the urban background stations is better than that of the GRAM model, one should acknowledge that the urban background concentration in the DMRB model is based on the measurements from the urban background stations, because the DMRB model needs them as part of the input data. Thus, the basis of the comparison at the urban background stations between the two models should be acknowledged. This is important when one considers action plans. One will need to consider differences in the traffic growth in London and Bangkok, which will change the background concentration. This is not easy to do in the DMRB model. The study also points to the significance of NO_2 in London. The measurements of the annual NO_2 mean at six out of eight sites violate the NO_2 objective. Five sites are located near roadsides and one site is in an urban background area closer to London centre than the other two urban background sites, where the NO_2 levels are within the standard. The other pollutants in Table 3.12 are well below their limit values.

The comparison of the two models against the measurements in Bangkok in 1998, as seen in Tables 3.14-3.15 and Figures 3.5-3.7, reveals that the performance of the GRAM model at the roadside sites is better than the DMRB model for the predictions of the annual mean NO_2, and the maximum 8-hour mean CO. The GRAM model gives the closer estimates and lower values of the root mean square difference (RMSD) than those of the DMRB model, whereas the DMRB model performs better than the GRAM model in the case of the annual mean PM_{10}. The GRAM model underestimates PM_{10} in Bangkok. There were no measurements of the annual mean C_6H_6 in Bangkok, so it was not included in the comparison. Though, the performance

of the DMRB model at the urban background sites appears to be better than that of the GRAM model, it is not a valid comparison as the DMRB model relies on background measurements. A standard for the annual mean NO_2 is not stipulated in Thailand. Therefore the World Health Organization guideline (WHO guideline) of 40 $\mu g\ m^{-3}$ was used to define its significance. Table 3.14 shows that the annual mean NO_2 concentrations at roadside sites in Bangkok breach the WHO guideline. As seen in Table 3.14, undoubtedly PM_{10} is a serious problem in Bangkok.

3.6 Possibility to alter the model to fit the conditions in Bangkok

Comparing the application of the DMRB model and the GRAM model, one finds a user-friendly computer program and less input data in the DMRB model. However when the output is considered, the DMRB model can provide only the predictions of the total concentration and road contribution, not of the urban concentration. While the GRAM model can estimate all of these factors. In the case of the DMRB model, if one wants to know the level of an air pollutant in a future year, one has to predict the future urban background concentration in that year beforehand and enter it as part of the input data into the DMRB model. So, the application of the DMRB model in the future years needs a model for predicting the urban background. This kind of function has been included in the GRAM model.

The development of the DMRB and GRAM models are based on the local conditions of London and/or the UK, which may not be applicable directly to local conditions elsewhere, for example to Bangkok conditions. To gain a good performance in the locally different areas, some internal parameters in the model inevitably have to be changed in order to fit with the new local conditions. This means the model should enable alterations of its formulae. The formulae in the GRAM model are kept in the original form of the Gaussian equations and all factors in formulae are known. Several formulae in the DMRB model can be modified to fit with the local conditions in Bangkok, e.g. the NO_x/NO_2 relationship, the year correction factor, etc. Whilst to change the Gaussian formulae for predicting road contribution in the DMRB model, known as the 'distance factor', one would need to modify a set of formulae, of which only the one variable of distance is specified in the model. This factor has been determined for UK conditions of meteorology and the emission rate of pollutants

emitted from a light duty vehicle (LDV). These may be different in local conditions. such as in Bangkok. The 'distance factor', therefore cannot be modified unless the original model is available from the Transport Research Laboratory (TRL). So the DMRB model is not a convenient model for modifying to a new model for Bangkok. together with the problem of predicting air quality in urban background areas in the future years. The DMRB model is not the first choice for the purposes of this research.

3.7 Summary

The DMRB and GRAM models meet all requirements in the criteria. The performance of the GRAM model is better than the DMRB model for the prediction of the road contribution of the annual mean NO_2, the maximum 8-hour mean CO, and the annual mean PM_{10} in London. In Bangkok the predicted PM_{10} factor is closer to the measurements when the DMRB model is applied, but the DMRB model is poor when it is used for estimating the NO_2. Part of the DMRB formulae has limitations if these are to be changed to fit with local conditions elsewhere, and it needs an external model for predicting one of its input data when one wants to know the future concentration in urban areas. The GRAM model is convenient for predicting in the future years concentrations at roadside and urban background sites in urban areas. The GRAM formulae are known and able to be changed to fit with other local conditions. Hence the GRAM model, a simple line source model, is selected for modification to an air model for assessing air quality in Bangkok. The results also reveal that the concentrations of NO_2 and PM_{10} in Bangkok should be of concern.

Chapter 4
Description of the GRAM Model

4.1 Introduction

This chapter explores the principal concepts, the model's structure, the formulae, and the model characteristics. The results of the chapter reveal the factors likely to need modification for developing an urban air quality model for Bangkok (hereinafter called the Bangkok GRAM model). The study of model characteristics shows the sensitivity of the prediction, and gives the user an awareness of the validity of each input parameter.

4.2 Methodology

4.2.1 Model's principal concept, the structure, and the formulae

The study in this section was based on the review of documents, e.g. Mathcad document (Fisher, 1999b), GRAM Model's electronic files (Fisher, 1998b). The concepts, structure, and formulae were systematically compiled and analysed.

4.2.2 Model characteristics

Model characteristics focus on the predictions of the road contribution to the annual mean of NO_2, C_6H_6, and PM_{10}, and the maximum 8-hour mean CO. Five sets of data, as shown in Table 4.1 were used. They are the traffic flow, the traffic speed, the heavy duty vehicle fraction (HDV fraction), and the distance from receptor to road centre line. When one factor was varied, the others were constant.

Table 4.1 Set of data for testing the model characteristics

Factor	Unit	Constant	Variation
Traffic flow	Vehicle/h	1000	100, 200, 500, 2000, 3000, 5000
Traffic speed	km/h	30	10,12, 14, 20, 30, 50, 60, 70, 80, 90, 100, 120, 150
HDV fraction	-	0.15	0.01, 0.02, 0.03, 0.05, 0.1, 0.3, 0.5
Distance from receptor to road centre line	m	10	3, 5, 20, 30, 50, 100, 200, 300

4.3 Results and discussion

4.3.1 The GRAM model's principal concept

The GRAM model is a simple computer model, or screening model, based on algorithms used in the American Gaussian-based roadside pollution model, the CALINE4 model, and the R91 model dispersion curves. The dispersion is based on

very stable conditions so that the lowest degree of mixing is considered. The model incorporates the DMRB methods for the vehicle emission factors, the year correction factors (the emission rate as a function of year), and vehicle speed correction factors. The GRAM model includes a long-term pollution model predicting the level of pollutants as an annual average and/or maximum values over the period of a year (Elsom, 1998, Fisher, 1999a, 1999b). The total concentration in the GRAM model is derived from the summation of the predicted roadside concentrations and the predicted background concentrations. The original GRAM model assumed that the emission density over urban area was uniform.

4.3.2 Structure of the GRAM model

The structure of the GRAM model is illustrated in Figure 4.1. The prediction of roadside concentration begins with the input data of traffic speed, and the present year to the year to be modelled, which are transferred via the DMRB correction factors and then separated into the "Speed correction factors" and the "Year correction factors" for the light duty vehicles (LDV) and the heavy duty vehicles (HDV). The percentage of HDV in the traffic fleet is also divided into the "Fraction of LDV" and the "Fraction of HDV". All factors relating to the LDV and the HDV are multiplied in their own group and then are summed to produce the "Effective LDV and HDV fraction" in the year to be modelled. In order to derive the "Relative roadside concentration", the roadside dispersion model needs the "Distance between the receptor and the road centre line" and the "Emission rate" as input factors. The emission rate, at this step, is the LDV emission rate travelling at 100 km/h. For VOC, the emission density and emission rate are converted, before entering to the dispersion model, to C_6H_6 with the assumption that C_6H_6 represents a 0.05 fraction of the VOC. The roadside dispersion model yields the "Relative roadside concentration". This value is multiplied by the "Traffic flow of the interest year" and the "Effective LDV and HDV fraction in the year to be modelled", to yield the "(actual) Roadside concentration". The GRAM model gives the results as the "Roadside short time mean concentration" of NO_x, CO, and PM_{10}, and the "Roadside annual mean concentration" of NO_x, C_6H_6, and PM_{10}.

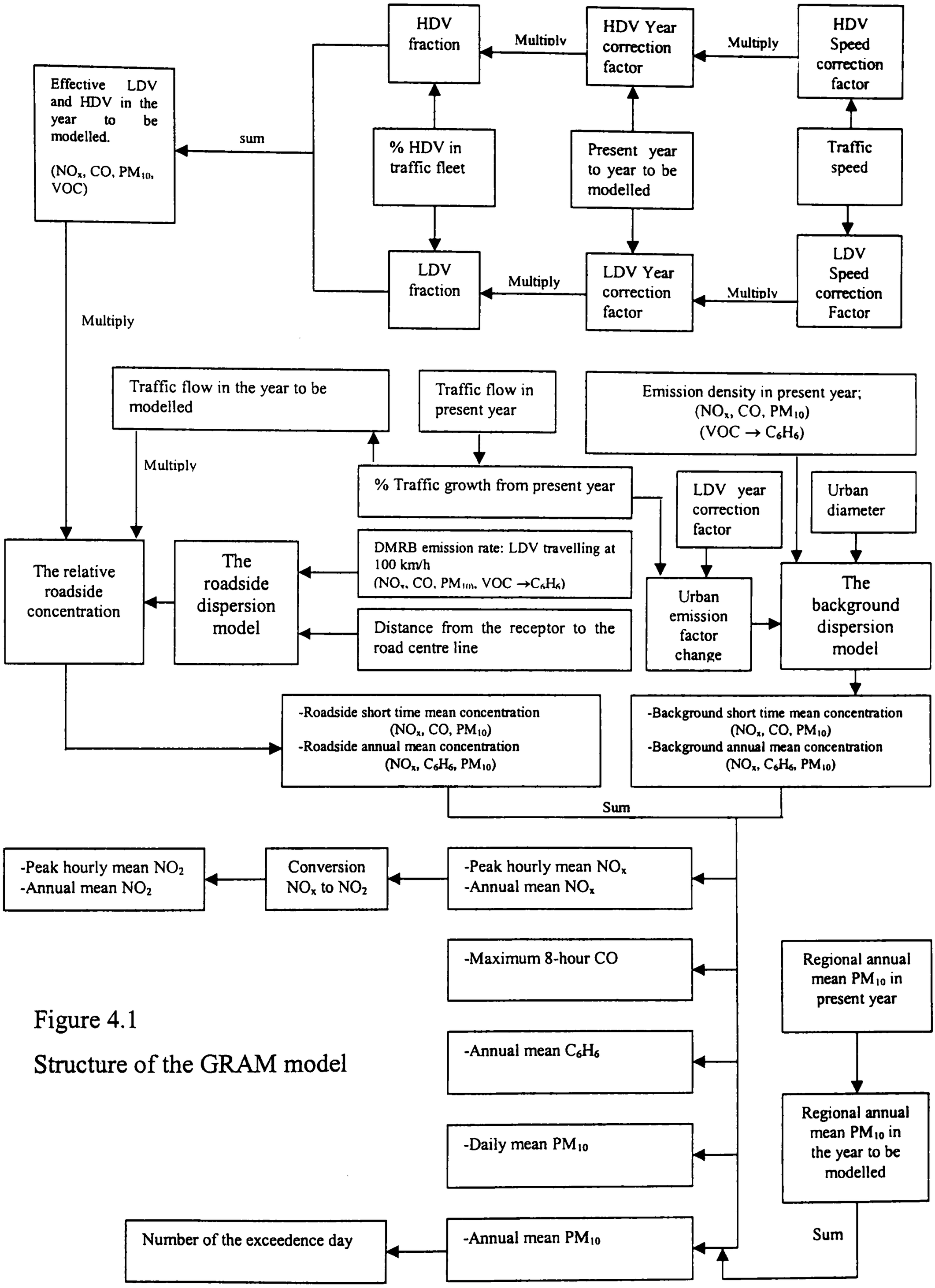


Figure 4.1

Structure of the GRAM model

The prediction of urban background in the GRAM model consists of the "Emission density in the present year", the "Urban diameter", and the "Urban emission factor change". The urban emission factor change is calculated from an equation with factors for the "LDV year correction factor" and the "Percentage of traffic growth from the present year". The results from the background dispersion model are the background concentrations in terms of the same averaging time as used by the roadside dispersion model.

Because the roadside and background dispersion models provide the output directly as required in the UK National Air Quality Objectives, the output data of the GRAM model does not need any further conversion to another form, except that the NO_x is required in the form of NO_2, and the annual mean PM_{10} needs the regional PM_{10} to be added. The number of exceedence days could be obtained from the annual mean PM_{10}.

4.3.3 Formulae in the GRAM model

The formulae used in prediction with the GRAM model can be divided into three groups: the roadside concentration, the background concentration, and the formulae related to the DMRB method as shown in Figure 4.1 and Box 4.1

The formulae of the roadside concentration can be divided into two sub-groups: the short term mean, and the long term mean. The formulae have the core structure following the line source Gaussian concept as:

$$C = (\text{const}Q)/(u\sigma_z(x))$$

Where const = a constant

Q = emission rate

u = wind speed

σ_z = vertical dispersion as a function of distance (x)

As shown in Box 4.1, in addition to the constant factor ($\sqrt{2/\pi}$), a factor of 1.5 is introduced to correct the peak hourly traffic flow from the annual average daily flow. The factor of ½ is included as a receptor is, on average downwind, of the road half of

the time. When the receptor is upwind of the road pollution from traffic in the road, emissions make no contribution to concentrations at the receptor position.

The effect of peak daily traffic flow of 1.5 is neglected in the daily mean PM_{10}, because it is unlikely that the worst dispersion conditions would last for 24 hours. The vertical dispersion, and wind speed used in the formulae are different in detail. The coefficients, *a, s* describing the vertical dispersion (σ_z) are set to represent the very stable condition class G for the short time mean formulae and to represent the neutral stability class D for the annual mean formulae. The short time mean formulae assumes a low wind speed of 1 m/s, while the annual mean formulae are based on a wind speed of 3 m/s. The short time mean formulae also incorporate a sigma zero (σ_{z0}) term to take account of the initial mixing produced by the moving vehicles.

The formulae of the background level are also divided into two sub-groups representing the short term mean, and the long term mean. The urban background formulae are derived from an area source Gaussian model applied to a circular urban area with an assumed uniform emission density (Fisher, 2000c). The formulae are similar in structure, but different in the constant factors used, as seen in the Box 4.1. The formulae incorporate a division factor for the conversion of ppb to $\mu g/m^3$ for NO_x and C_6H_6, and ppm to mg/m^3 for CO. The urban emission factor change (B) is the function of the LDV's year correction factor, and the percentage of traffic growth from the present year. The emissions in the formulae assume that a fraction of 0.7 originates from the traffic, which changes according to the traffic growth and the year correction factor. The remaining fraction of the emission of 0.3 is assumed to arise from non-transport sources, which are assumed not to change in the future.

Because the prediction gives the results as NO_x, whereas the concentration required in the UK National Air Quality Objectives is NO_2. Thus, the conversion from NO_x to NO_2 is included in the final step. The GRAM model provides the relationship between NO_x and NO_2 in two options as shown in Box 4.2. The Option 1 is an empirical relationship based on the Derwant-Middleton curve applied to NO_x concentrations no greater than 1000 ppb (Fisher, 1999b). Concentrations greater than 1000 ppb only occur during an unusual episode when NO concentrations are very high, when the NO

+ NO reaction is important in NO_2 production. The empirical curve in the Option 1 is derived from the measured hourly average roadside concentrations in London. The Option 2 is derived from an equilibrium between NO_2, NO, and O_3 under photochemical reaction. This option applies to any NO_x concentration (Fisher, 1999b). The theoretical curve in the Option 2 is also used in the CALINE4 model (Fisher, 2000d). The year and speed correction factors from the DMRB methodology are shown in Box 4.3.

Box 4.1 Formulae in the GRAM model

Roadside concentration = Flow x Normal(distance) x $[(YF_{LDV} \times FrcLDV \times SF_{LDV}) + (YF_{HDV} \times FrcHDV \times SF_{HDV})]$
Total concentration[1] = Roadside concentration + Background concentration
Total concentration[2] = Roadside concentration + Background concentration + Regional concentration
Note 1. for NO_x, CO, and C_6H_6
2. for PM_{10}

Formulae of the roadside concentration

Normal (distance) for the short time mean	Peak hourly NO_x Maximum 8-hour CO	$\frac{1.5\ constQ}{u\ \sigma_z(x)}$	$\sigma_z(x) = ax^s + \sigma_{z0}$ u = 1 m/s $\sigma_{z0} = 1$ a = 0.151, s = 0.557 const = $\sqrt{2/\pi}$
	Daily mean PM_{10}	$\frac{const\ Q}{u\ \sigma_z(x)}$	
Normal(distance) for the long time mean	Annual mean NO_x Annual mean C_6H_6 Annual mean PM_{10}	$\frac{constQ}{2u\ \sigma_z(x)}$	$\sigma_z(x) = a(27+x)^s$ u = 3 m/s a = 0.08, s = 0.865 const = $\sqrt{2/\pi}$

Formulae of Background concentration

Short time mean	Peak hourly NO_x	$\frac{Bq157.748L^{0.483}}{1.95}$	$B = [0.7\ F(year)\{1+(P/100)\}^{(year\ -\ 1996)} + 0.3]$
	Maximum 8-hour CO	$\frac{Bq157.748L^{0.483}}{1165}$	
	Daily mean PM_{10}	$Bq157.748L^{0.483}$	
Long time mean	Annual mean NO_x	$\frac{Bq13.138L^{0.413}}{1.95}$	
	Annual mean C_6H_6	$\frac{Bq13.138L^{0.413}}{3.24}$	
	Annual mean PM_{10}	$Bq13.138L^{0.413}$	
	Annual daily exceedence PM_{10}	$3.219(AnnPM_{10} - 15.6) + 4$	

where
Q is the emission rate in μg/m/s/(veh/day) based on the base year correcting from an emission factor in g/km x 1000000/(1000 x 3600 x 24)
Const is the constant of $\sqrt{2/\pi}$ arising from the Gaussian formula.
u is the wind speed in m/s.
$\sigma_z(x)$ is the vertical dispersion.
σ_{z0} is the initial mixing produced by vehicle wakes.

a, s are the parameters describing vertical dispersion.
B is the urban emission change, which depends on year and traffic growth
q is the emission density in $\mu g/m^2/s$.
L is the urban diameter in km.
P is the % traffic growth rate.
YF_{LDV}, F(year) are the DMRB's year correction factor for LDV.
YF_{HDV} is the DMRB's year correction factor for HDV.
SF_{LDV} is the DMRB's speed correction factor for LDV.
SF_{HDV} is the DMRB's speed correction factor for HDV.
FrcLDV is the LDV fraction in traffic flow.
FrcHDV is the HDV fraction in traffic flow.

Box 4.2 Conversion of NO_x to NO_2 in the GRAM model

Option	The formulae for the conversion of NO_x to NO_2	
Option 1 (use for NO_x concentration no greater than 1000 ppb)	$NO_2 = const + bNO_x + cNO_x^2 + dNO_x^3$	Const = 7.2769 b = 0.2736 c = 5.10366×10^{-4} d = 4.4561×10^{-7}
Option 2 (Apply to any NO_x concentration)	$NO_2 = \frac{T - \sqrt{T^2 - 4NO_x O_x}}{2}$	$T = NO_x + O_x + Z$ $O_x = 20 + 0.05NO_x$ $Z = k_r/k_f$ $k_r = 4*10^{-3}$ $k_f = 0.0517*\exp(-1450/(temp+273))$ temp = 15°C

where
b, c, and d are the coefficients.
T is the summation of total NO_x, O_3, and photostationary constant.
O_x is ozone, for which a background concentration of 20 ppb ozone is assumed.
Z is the photostationary constant.
k_r is the backward rate constant.
k_f is the forward rate constant.
temp is the temperature in °C.

Box 4.3 Formulae of the year correction factor and the speed correction factor

$YF_{NOx\text{-}LDV}$	=	$4.41 +(0.153T)-(0.00151T^2)-(5.76/T)+(2.19/T^2)-(2.16\ln(T))$	
$YF_{NOx\text{-}HDV}$	=	$25.2+(0.317T)-(29.5/T)+(12.9/T^2)-(9.07\ln(T))$	
$SF_{NOx\text{-}LDV}$	=	$0.676-(0.00565S)+(0.00009S^2)+(0.22/S)$	(when traffic flow > 0)
$SF_{NOx\text{-}HDV}$	=	$1.02-(0.0143S)+(0.000117S^2)+(23.9/S)-(33.6/S^2)$	(when traffic flow > 0)
$YF_{CO\text{-}LDV}$	=	$1.84 +(0.0255T)-(0.883/T)-(0.713\ln(T))$	
$YF_{CO\text{-}HDV}$	=	$0.837+(0.00967T)-(0.67/T)+(0.258/T^2)-(0.272\ln(T))$	
$SF_{CO\text{-}LDV}$	=	$1.74 -(0.0438S)+(0.000353S^2)+(14.2/S)$	(when traffic flow > 0)
$SF_{CO\text{-}HDV}$	=	$-0.115+(0.007S)+(42/S)-(41.8/S^2)$	(when traffic flow > 0)
$YF_{HC\text{-}LDV}$	=	$4.78 +(0.178T)-(0.00183T^2)-(6.38/T)+(2.42/T^2)-(2.4*\ln(T))$	
$YF_{HC\text{-}HDV}$	=	$29.2+(0.727T)-(0.00649T^2)-(67.4/T)+(68.8/T^2)-(29.4/T^3)-12.5*\ln(T)$	
$SF_{HC\text{-}LDV}$	=	$2.4-(0.041S)+(0.000245S^2)+(27.7/S)$	(when traffic flow > 0)
$SF_{HC\text{-}HDV}$	=	$0.139+(0.00335S)+(51.7/S)$	(when traffic flow > 0)
$YF_{PM10\text{-}LDV}$	=	$3.59 +(0.0937T)-(0.000719T^2)-(4.41/T)+(1.73/T^2)-(1.6\ln(T))$	
$YF_{PM10\text{-}HDV}$	=	$22.7+(0.0197T^2)-(0.000358T^3)-(14.6/T)+(3.31/T^3)-(8.46\ln(T))$	
$SF_{PM10\text{-}LDV}$	=	$1.25-(0.00956S)+(0.000071S^2)+(11.3/S^2)$	(when traffic flow > 0)
$SF_{PM10\text{-}HDV}$	=	$0.657-(0.00456S)+(0.000043S^2)+(37.2/S)$	(when traffic flow > 0)

where
$YF_{NOx\text{-}LDV}$ is the year correction factor for prediction of NO_x emitted from LDV.
$YF_{NOx\text{-}HDV}$ is the year correction factor for prediction of NO_x emitted from HDV.
$YF_{CO\text{-}LDV}$ is the year correction factor for prediction of CO emitted from LDV.
$YF_{CO\text{-}HDV}$ is the year correction factor for prediction of CO emitted from HDV.
$YF_{HC\text{-}LDV}$ is the year correction factor for prediction of HC emitted from LDV.
$YF_{HC\text{-}HDV}$ is the year correction factor for prediction of HC emitted from HDV.
$YF_{PM10\text{-}LDV}$ is the year correction factor for prediction of PM_{10} emitted from LDV.
$YF_{PM10\text{-}HDV}$ is the year correction factor for prediction of PM_{10} emitted from HDV.
$SF_{NOx\text{-}LDV}$ is the speed correction factor for prediction of NO_x emitted from LDV.
$SF_{NOx\text{-}HDV}$ is the speed correction factor for prediction of NO_x emitted from LDV.
$SF_{CO\text{-}LDV}$ is the speed correction factor for prediction of CO emitted from LDV.
$SF_{CO\text{-}HDV}$ is the speed correction factor for prediction of CO emitted from LDV.
$SF_{HC\text{-}LDV}$ is the speed correction factor for prediction of HC emitted from LDV.
$SF_{HC\text{-}HDV}$ is the speed correction factor for prediction of HC emitted from LDV.
$SF_{PM10\text{-}LDV}$ is the speed correction factor for prediction of PM_{10} emitted from LDV.
$SF_{PM10\text{-}HDV}$ is the speed correction factor for prediction of PM_{10} emitted from LDV.
T is the number of years from the base year.
S is the average vehicle speed in km/h.

4.3.4 Model's factors needing modification

Traffic data in the model are the flow, the speed, the HDV fraction, and the percentage traffic growth, all of which are included in the input data. Hence, the new model can keep these as in the original model. However, the conditions for these factors in Bangkok have to be known for establishing a set of scenarios. The distance between a receptor and the road centre line can be obtained from a site survey. We can get the emission density from an atmospheric emission inventory. However, the measurements from urban background sites, as shown in Chapter 3, reveal that the concentrations at those sites vary in accordance with the distance from urban centre, the further from the centre the lower the concentration. Hence, the predicted uniform concentration throughout the urban area does not seem to be a good representative of concentration.

In the case of the internal parameters, most of them are assumed to be different from those in Bangkok due to the local conditions. The factors are the peak hourly traffic flow used to correct the annual daily flow for the calculation of the peak hour NO_x and the maximum 8-hour CO, the wind speeds for predicting roadside contributions in the short term and annual means, the NO_2/NO_x empirical relationship, the NO_2/NO_x theoretical relationship which relate to the ambient temperature; the background ozone in the area; and the primary NO_2 from mobile sources, and the fraction of mobile and non-mobile sources.

The vehicle emission factors of the light duty vehicles (LDV) and the heavy duty vehicles (HDV) are developed from the emission rate of a light duty vehicle travelling at 100 km/h in the base year of 1996. The vehicle emission factors of heavy duty vehicles are expressed relative to the emission factor of a light duty vehicle in the base year 1996. The emission factors of the light duty vehicles are based on the emission standards implemented on the vehicle fleet during the base year. The introduction of most of the EU emission limit values in the Thailand is later than that of the UK by several years, for example the 96/69/EC Directive. Some emission standards, e.g. the 83/351/EEC Directive, were implemented in UK but not in Thailand, and some in Thailand but not in the UK, e.g. the 88/76/EEC Directive. Hence the emission rate of a light duty vehicle travelling at 100 km/h in Bangkok in 1996 and later years seems to be different to the DMRB's values. The year correction

factor is based on the fleet composition, the emission rate of vehicle types beyond the base year, and the traffic growth rate in the area, all of which are expected to be different under conditions in Bangkok. The speed correction factor is the ratio of vehicle emission travelling at other speeds compared to 100 km/h. This factor is not based on the local conditions, so it is assumed to be the same in Thailand.

4.3.5 Model characteristics

As seen in Figure 4.2, the GRAM model predictions of the road contributions of NO_2, CO, C_6H_6, and PM_{10} at the distance of 10 m from the road centre line increase evenly, as the traffic flow increases. The increase of NO_2 is a non-linear curve because the model includes NO_x to NO_2 conversion, which is a non-linear relationship. The predictions of the road contribution of the maximum 8-hour mean CO, the annual mean C_6H_6, and the annual mean PM_{10} are in direct proportion to traffic flow, as shown in Figure 4.2 by linear curves.

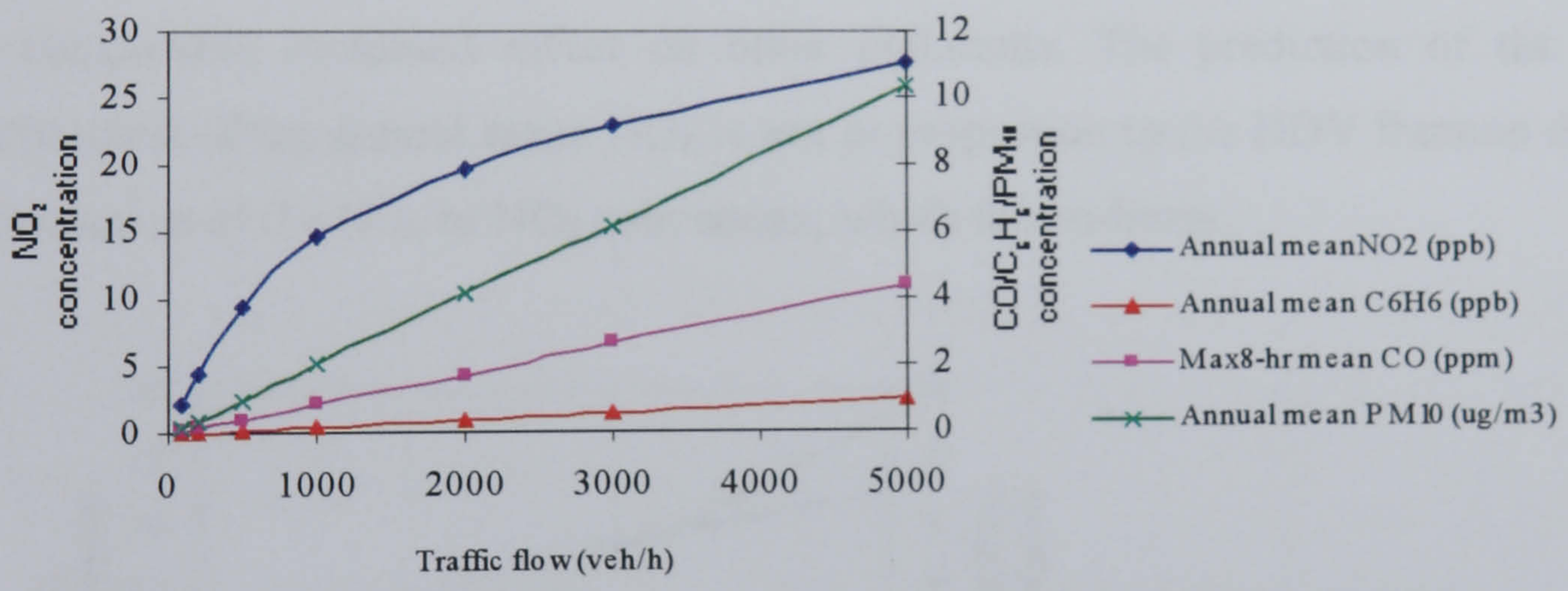


Figure 4.2 Road contribution and traffic flow variation

The model predictions as displayed in Figure 4.3 are non-linear curves. The road contributions of the annual mean NO_2, and maximum 8-hour mean CO decreases, when the traffic speed increases in the range of 5 to 70 km/h. When the traffic speeds reach 80 km/h, the predictions of the road contribution of these pollutants start to increase, whilst the annual mean of C_6H_6 and PM_{10} decrease when the traffic speed increases in the range of 5 to 90 km/h. When the traffic speed reaches 100 km/h, the road contributions of the annual mean of C_6H_6 and PM_{10} start to increase.

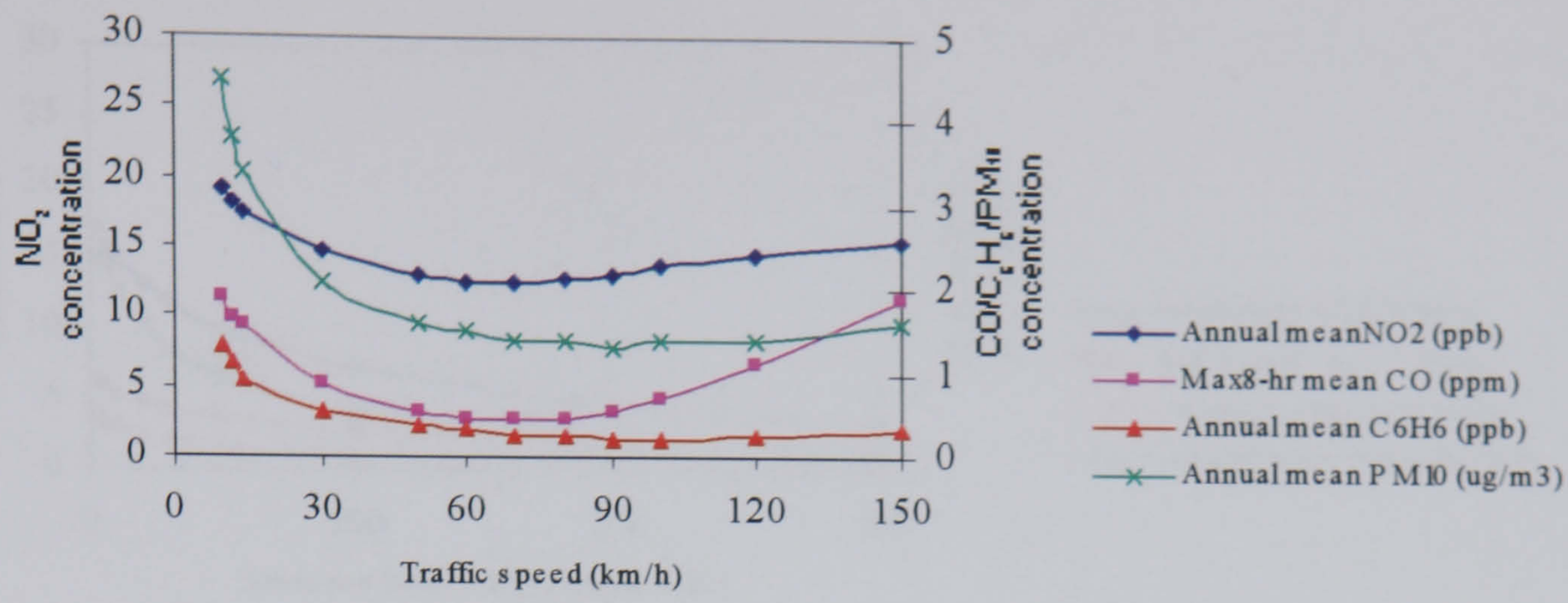


Figure 4.3 Road contribution and speed variation

The prediction of road contribution of the annual mean of NO_2, C_6H_6, and PM_{10} increases continuously, when the fraction of heavy duty vehicle (HDV fraction) in the vehicle fleet increases as seen in Figure 4.4. On the contrary, the prediction of road contribution to the maximum 8-hour mean CO decreases continuously, when the HDV fraction in the vehicle fleet increases. However, the increase of the HDV fraction gives a lower effect on the reduction of the maximum 8-hour mean CO, than the comparable increased effect on other pollutants. The prediction of the road contribution of the annual mean NO_2 is not in proportion to the HDV fraction due to the inclusion of the NO_x to NO_2 conversion, which is non-linear.

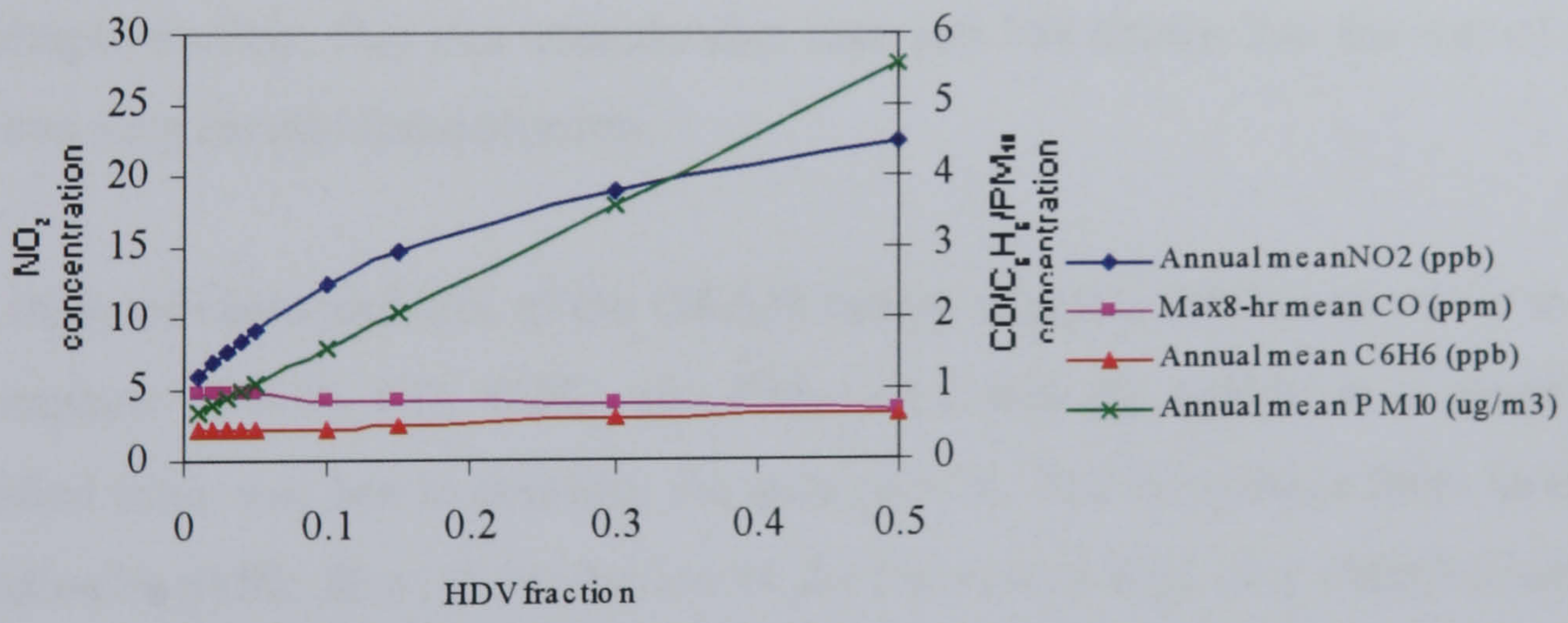


Figure 4.4 Road contribution and HDV fraction variation

The model predicts that the road contributions of the annual mean NO_2, the maximum 8-hour mean CO, the annual mean C_6H_6, and the annual mean PM_{10} are not in proportion to distance from the road centre line. The predictions decrease along non-linear curves, when the distance between the receptor and the road centre line increases as illustrated in Figure 4.5.

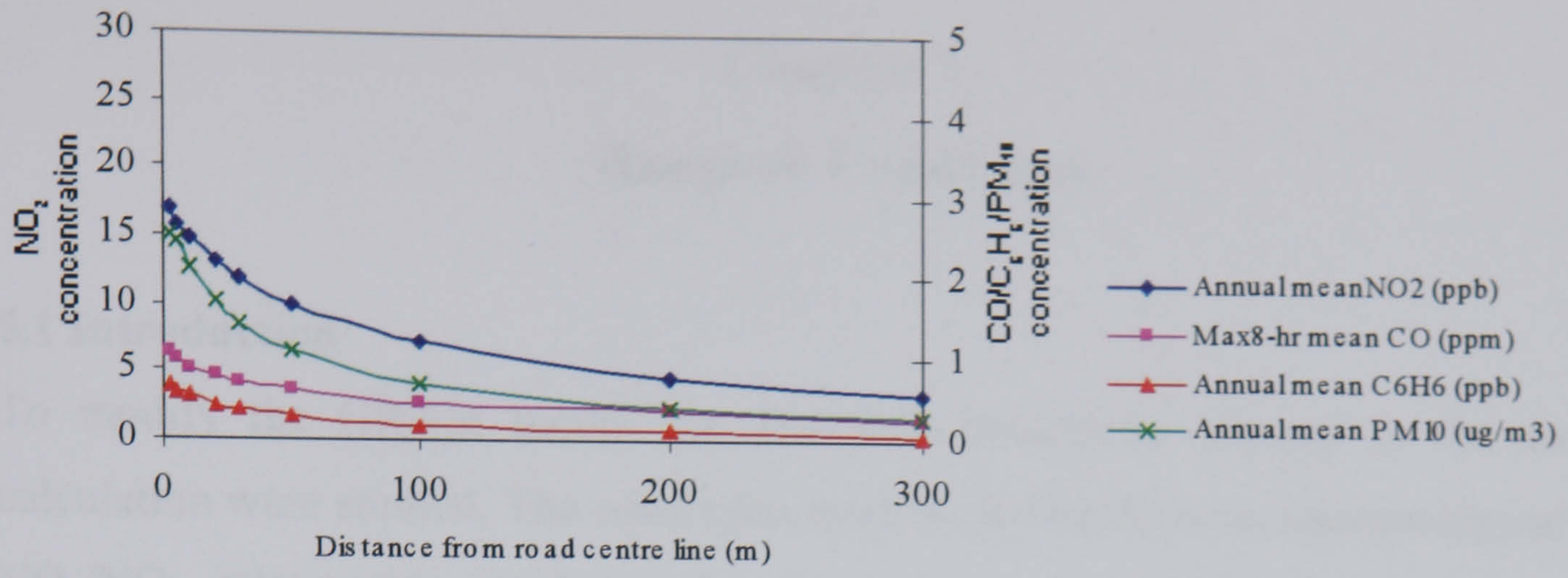


Figure 4.5 Road contribution and distance variation

The results as shown in Figures 4.2 – 4.5 suggest that changes in each factor influence the prediction values. Hence the collection of the input data should be done carefully to ensure their accuracy.

4.4 Summary

The GRAM model is a simple model developed under the UK conditions, with a limited number of parameters, compared with many air pollution models currently available. Formulae of all parameters are known and can be altered to fit with local condition elsewhere. However, this chapter shows very clearly that before considering the use of a model a very detailed review of its basis should be undertaken. Even for the simple models, this is a considerable task and has shown that the use of models requires very careful consideration.

The study of characteristics of the GRAM model suggests that if one wants to reduce the impacts of NO_2, CO, C_6H_6, and PM_{10} on urban air quality at a receptor at a specified time, one has to consider the strategies on how to manage three factors: the reduction in traffic flow, the reduction in the fraction of high duty vehicle (not for the case of CO) on the vehicle fleet, and the increase in traffic speed to a limit that is no faster than 100 km/hr. However, more studies should be carried out on the comparison of those three factors. To find out which factors are more practical than others, one needs to consider other issues, such as the effectiveness, the cost-benefit, the likelihood of community agreement, and the practicality.

Chapter 5

Bangkok Conditions

5.1 Introduction

To modify the GRAM model, the Bangkok conditions relevant to the model's calculation were studied. The conditions covered the traffic data, meteorological data, NO_x/NO_2 relationship, emission density, resuspended dust, regional background PM_{10}, and 'Year Correction Factor (YCF)'. Because of the various contexts to this chapter, each section contains subsections of the literature review, the methodology, the results and discussion.

5.2 Traffic data

The relevant traffic data are the growth rate, the percentage of 'Heavy Duty Vehicles (HDV)', and the average fraction of traffic flow during the peak hour. The first two factors are the input data, whereas the last one is an internal parameter for calculating a short term mean such as the peak hourly NO_x, and maximum 8-hour CO. However, it is not included in the model modification in this research.

5.2.1 Traffic growth rate

Road vehicles are registered under three Acts: the Motor Vehicle Act, the Land Transport Act, and the Non-Motorised Vehicle Act under the Department of Land Transport (MOTC, 1999; Department of Land Transport, 2004). The traffic growth rate in Bangkok was obtained from the number of registered vehicle during 1989-2003. The vehicles under the Motor Vehicle and Land Transport Acts are categorised into 16 types, and six types respectively, and they were re-classified into groups labelled Car, Van and Pick up, Bus, Truck, Motorcycle, and others, as shown in Table 5.1. The grand total of vehicles, percentage growth rates and the latter classes of vehicles in Bangkok are estimated, and shown in Table 5.2.

Table 5.1 Vehicle classification

Act[(a)]	Classification [(a)]	Re-classification
Motor Vehicle Act	Sedan (Car)	Car
	Interprovincial Taxi	
	Urban Taxi	
	Fixed route Taxi	
	Hotel Taxi	
	Tour taxi	
	Car for hire	
	Microbus and Passenger van	Van and Pick up
	Van and Pick up	
	Motorcycle	Motorcycle
	Tractor	Others
	Road roller	
	Farm's vehicle	
	Automobile's Trailer	
	Motortricycle	
	Motortricycle Taxi (Tuk Tuk)	
Land Transport Act	Fixed route Bus	Bus
	Non-fixed route Bus	
	Private Bus	
	Small Rural Bus	
	Non-fixed route Truck	Truck
	Private Truck	

Source: (a) = Department of Land Transport (2004)

Table 5.2 Total number and percentage of vehicle composition in Bangkok

Year	Grand total	Percentage						
		Growth rate	Car	Van and Pick up	Bus	Truck	Motorcycle	Others
1989	1721586	N/A	29.2	27.2	1.1	3.4	37.4	1.7
1990	2045814	18.8	30.8	27.8	1.0	3.3	35.6	1.5
1991	2112518	3.2	29.7	22.8	1.1	3.7	42.0	0.7
1992	2373288	12.3	28.9	23.5	1.0	3.6	42.4	0.6
1993	2656107	11.9	28.8	24.0	0.9	3.4	41.6	1.3
1994	2963043	11.6	31.5	22.0	0.8	2.8	41.6	1.2
1995	3241081	9.4	30.6	22.3	0.8	2.8	42.4	1.1
1996	3549082	9.5	30.5	22.0	0.7	2.8	43.0	1.0
1997	3872327	9.1	31.2	22.5	0.7	2.9	41.7	1.0
1998	4016594	3.7	32.1	22.7	0.6	2.6	41.0	1.0
1999	4162846	3.6	33.2	22.9	0.6	2.4	39.9	1.1
2000	4468977	8.0	29.4	23.1	0.6	2.3	44.0	0.6
2001	4464158	-0.7	31.5	23.0	0.7	2.8	41.5	0.4
2002	5399153	20.9	31.5	21.7	0.6	2.3	43.6	0.3
2003	5481160	1.5	34.0	20.1	0.6	1.9	43.2	0.3

Sources: Modified from MOTC (1999); Department of Land Transport (2004)

N/A = not available

The results in Table 5.2 show that the total vehicle fleet in Bangkok grew from 1.72 million vehicles in 1989 to 4.02 million vehicles in 1998 (MOTC, 1999; Department of Land Transport, 2004). The growth over this 10-year period was around 133%. More recently the number of vehicles in Bangkok has reached 5.5 million (Department of Land Transport, 2004). The annual vehicle growth rate in Bangkok before 1997 was generally more than 9%. After Thailand's economic crisis in 1997, the traffic growth rate in Bangkok was unpredictable. However, the growth rate of national road vehicle between 2001and 2003 was about 8-9% (Department of Land Transport, 2004). In addition, the number of brand new vehicles of type Car, Van and Pick up, and Motorcycle, registered in Bangkok during January to June 2004 is more than 320 thousand (Department of Transport, 2004). This means it is not unlikely that the growth rate in 2004 may reach 9%. Hence for this research, the normal growth rate of 9% was adopted for estimating the concentration of pollutants under current policy on emission reduction. Compared to the same period, Londoners owned a total of 2.36 million vehicles in 1989 (DETR, 2000) and increasing to 2.86 million vehicles in 2002 (DfT, 2003). The statistics indicated that vehicle growth rate in London in 2001 was around 1.9% and dropped to 0.4% in 2002 (DfT, 2002, 2003). The decline seems to come from congestion limiting the mobility advantages of private transport, rather than strategies introduced in London to switch the travel mode from car to public transport.

5.2.2 Percentage of the heavy duty vehicle (%HDV)

This factor is the combination of "Bus" and "Truck" categories, and was determined from vehicle registration and traffic surveys. The traffic composition in Bangkok is surveyed by the Department of Traffic and Transport, Bangkok Metropolitan Administration (BMA) at major junctions during 07.00 a.m. to 07.00 p.m. (Traffic and Transportation department, BMA, 2004). However, the Motorcycle category is not included in the survey. The 2003/2004 surveys at the roads passing three roadside air quality monitoring stations were taken in this research and compared against the percentage of heavy duty vehicles in the registered road vehicle fleet.

Table 5.3 shows the similarity of heavy duty vehicle fractions in the survey and national records. So, it was assumed that the percentage of heavy duty vehicles amongst registered vehicles could be applied to the real traffic volume. Hence, in

accordance with Table 5.2, the heavy duty vehicle fraction of 0.03 (3%) was used for the predictions of future years. The 2000-2002 records from the Department for Transport indicated that the percentage of heavy duty vehicle registered in London was about 1.2-1.3% (DfT, 2001, 2002, 2003), dissimilar to the 2003 surveys on Marylebone Road which is 12% (Environmental Research Group, King College, 2004).

Table 5.3 Comparison of HDV fraction in traffic surveys and registered vehicles in Bangkok

Road	Air monitoring station	Total number (exempt MC)	Bus	Truck	HDV fraction
Maepra church junction, Dindaeng Rd.	Dindaeng	88890	2541	1654	0.047
Chokchai 4 junction, Ladphrao Rd.	Ladphrao	58233	3177	607	0.065
Terdthai junction, Intrapituk Rd.	Thonburi Electricity	47994	2142	422	0.053
Registered vehicle in 2000	-	2502627	26814	102786	0.052
Registered vehicle in 2001	-	2687821	28798	110393	0.052
Registered vehicle in 2002	-	3045122	32395	124181	0.051
Registered vehicle in 2003	-	3114179	33026	102143	0.043

Source: (a) Traffic and Transportation Department, BMA (2004)
(b) Department of Land Transport (2004)
Note: MC = Motorcycle

5.3 Meteorological data

Bangkok, the capital of Thailand, is in the central part of the country where the topography is a large low plain. The location of Thailand is in the tropical area between latitudes 5° 37'N to 20° 27'N and longitudes 97° 22'E to 105° 37'E (Meteorology Department, 2001a). The tropical area, where the location is between 23.5 North and 23.5 South, is the area where the Sun is vertical at noon, the seasonal changes in sun's position are small, and day length always near 12 hours (Hipps, 2002). The climate and seasons of Thailand (Meteorology Department, 2001a, 2003) are under the influence of monsoon winds: southwest and northeast monsoons (Meteorology Department, 2001a). The influence of monsoons arises during three seasons. The rainy season of the southwest monsoon is during mid-May to mid-October. The winter season of the northeast monsoon season is from mid-October to mid-February. The summer or pre-monsoon season lasts from mid-February to mid-May. The meteorological factors involved in the predictions of the GRAM model are temperature, wind speed and the fraction of stagnant conditions (calm winds).

5.3.1 Temperature

Temperature is a function of the photostationary constant (Z) used in the conversion of NO_x to NO_2 in the GRAM model. The model set the temperature of 15°C for a calculation of NO_2 in the UK. The meteorological parameters are monitored as part of a national data set by the Meteorological Department at the Don Muang Airport and the Bangkok meteorological station. However, the Department of Pollution Control (PCD) also observes some meteorological parameters at most of the air quality monitoring stations (PCD, 1999). According to a recommendation, at least three years of meteorological data are required for predicting long-term concentrations, such as the annual mean, or percentile (DETR, 1998). For the case of temperature in Bangkok, the years 1996 to 1998 were chosen and the months of March, June, and November were selected as the representative of the summer, rainy, and winter seasons. The hourly data at the Bangkok station were used. The monthly maximum, minimum and average temperature were identified in the overview of temperatures in Bangkok.

Table 5.4 Temperature observed in Bangkok between 1996 and 1998 (degree Celsius)

Temperature	Mar-96	Jun-96	Nov-96	Mar-97	Jun-97	Nov-97	Mar-98	Jun-98	Nov-98
maximum	33.0	33.9	32.7	35.0	36.0	36.0	nd	36.0	33.0
minimum	23.0	24.2	22.1	23.0	24.0	24.0	nd	25.0	25.0
average	28.2	29.0	27.7	29.1	30.6	29.3	nd	31.1	29.2

Source: Meteorology Department (1999)

Table 5.4 shows that the maximum, minimum, and average temperatures in Bangkok during 1996 - 1998 are around 33 - 36°C, 22- 25°C, and 28 - 31°C respectively. Hence this research used the average temperature of around 30°C for the air quality predictions in Bangkok.

5.3.2 Wind speed and stagnant wind fraction

Wind is one of the main factors in diluting the pollutants in the air. Stronger winds lead to less concentration of pollution. While calm winds mean a poor diluting condition may exist in the area. The GRAM model used the wind speeds of 1 m/s in calculating the short term peak mean, such as the 8-hour mean, and the 24-hour mean, and 3 m/s for the annual mean. In a later version, the GRAM model included the stagnant wind (0.0-0.5 m/s) fraction for estimating the road contribution at locations where calm winds might be a large fraction of the wind pattern. In the case of winds,

observations undertaken by the Pollution Control Department were selected so as to get the data on pollutant levels and winds at the same location. The wind data from eight air quality monitoring stations located in Bangkok and three suburban stations during 1997-1999 were used. The winds were categorized into the ranges of 0.0-0.5, 0.5-2.0, 2.0-3.0, 3.0-5.0, 5.0-8.0, 8.0-11.0 m/s, and greater than 11.0 m/s. The annual wind speed of each station in individual years was also studied. The wind fraction in each range of speed over the three year was obtained. Hence the fraction of stagnant winds in Bangkok was taken from the frequency of winds in the range of 0.0-0.5 m/s. and the wind speeds for short-term mean and annual mean of Bangkok were analysed and compared with the winds used in the original GRAM model.

Table 5.5 shows that the average of the calm or stagnant wind (0.0-0.5 m/s) fraction observed between 1997-1999 from 11 air quality monitoring stations in Bangkok and its suburbs is about 0.2. The annual mean wind speed range is between 0.7 - 2.3 m/s. Around 60% of wind speed fall into the category of 0.5-2.0 m/s. Thus, most of the annual mean wind speeds were less than 2 m/s, except those measured at the stations at Ramkhumhaeng and the Meteorology Department. From field surveys, it was found that these two stations are located in open areas, while most of the other rest stations are surrounded by the high buildings or wind obstructions. Around 12% and 5% of winds are in range of 2.0-3.0 and 3.0-5.0 m/s respectively. For a few hours, winds are greater than 5 m/s. These ranges of wind speed occur during the daytime, and are stronger during the summer and rainy seasons. These stronger winds promote the dilution of air pollution after the morning peak emissions and at later times of the day.

In the original GRAM model, the wind speeds of 1 m/s and 3 m/s were used for estimating the short term mean and the annual mean respectively. The results show that the frequency of winds of 3 m/s and more in Bangkok is less than 5%. The wind speed for the annual mean prediction should then be lower than 3 m/s. The results show that more than 60% of winds were less than 2 m/s, and the frequency of stronger winds over 2 m/s was around 17%. However, the latter group of winds occurred during the period of high pollution when these winds should influence the dilution of air pollution. As a first attempt, the mean wind speed was taken to be 2 m/s. The wind speed of 1 m/s for the prediction of short-term mean would correspond to the lower range of wind speeds found in Bangkok.

Table 5.5 Wind speed at air quality monitoring stations in Bangkok and suburban region

Station	Year	Number of hour at wind speed range							Total observed hour	Annual mean wind speed (m/s)
		0.0-0.5 m/s	0.5-2.0 m/s	2.0-3.0 m/s	3.0-5.0 m/s	5.0-8.0 m/s	8.0-11.0 m/s	>11.0 m/s		
Ramkhumhaeng, Bangkok	1997	1103	3212	2157	1804	134			8410	2.07
(East)	1998	1229	2768	1956	1934	90	2		7977	2.08
	1999	1268	3012	1471	1742	215	1		7709	2.03
Klong Jun, Bangkok	1997	736	6462	1398	156				8752	1.44
(North East)	1998	920	6604	1091	39				8654	1.34
	1999	1213	6434	937	71				8655	1.28
Nonsi, Bangkok	1997	2215	5924	491	117				8747	1.01
(South East)	1998	2498	5201	239	34				7972	0.86
	1999	2808	5067	294	42				8211	0.87
Singharach, Bangkok	1997	1669	5841	1220	24				8754	1.22
(South West)	1998	1465	5244	1349	25	2			8085	1.28
	1999	1371	5832	842	19				8064	1.16
Ladphrao, Bangkok	1997	2177	5193	505	132	1			8008	0.99
(North East)	1998	2296	5213	318	17				7844	0.92
	1999	3671	4672	79					8422	0.70
Dindaeng, Bangkok	1997	1596	6780	188	6				8570	0.93
(North East)	1998	3334	4648	83	2		1		8068	0.72
	1999	1948	5039	3	117				7107	0.83
Thonburi Electricity, Bangkok	1997	1580	5897	1146	122				8745	1.30
(South West)	1998	2233	5503	990	28				8754	1.17
	1999	2411	4636	591	40				7678	1.06
Meteorology Department,	1997	401	4433	2159	1458	19			8470	2.25
Bangkok	1998	405	3131	1359	630	1			5526	2.07
(East)	1999	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Samutsakorn,	1997	833	5601	1950	331				8715	1.52
Samutsakorn Province	1998	2409	5736	427	6	2			8580	0.98
(South West)	1999	2445	5533	495	10				8483	0.98
Department of Medical Science,	1997	553	3346	1098	392	1			5390	1.60
Nontaburi Province	1998	959	3660	1584	394				6597	1.57
(North West)	1999	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rungsit,	1997	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Prathumthaini Province	1998	485	2535	817	274	3			4114	1.56
(North)	1999	521	3424	1297	633	48			5923	1.74
Observed hour	1997-1999	48752	146581	28534	10599	516	4	0	234984	-
Wind fraction	1997-1999	0.2	0.6	0.1	0.0	0.0	0.0	0.0	-	-

Note: N/A = not available

5.4 NO_x and NO_2 relationship

NO_2 is produced by the chemical reactions of NO and O_3 or O_2. The reaction between NO and O_2 only occurs during episodes of extremely high NO. The main mechanism is the reaction between NO and O_3 (Highways Agency, 1999).

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

During the daytime, NO_2 absorbs blue and UV radiation (< 420 nm) (Colls, 1997) and decomposes back to NO and the oxygen radical (O). That radical reacts with O_2 to form O_3, then O_3 reacts with NO to form NO_2 and release O_2 (Nevers, 1995). The $NO/NO_2/O_3$ system is reactive on the timescale of seconds. The reaction processes are as following (Harrison, 1997):

$$NO_2 \xrightarrow{\text{Solar radiation}} NO + O$$

$$O + O_2 \longrightarrow O_3$$

$$NO + O_3 \longrightarrow NO_2 + O_2$$

In the Gaussian approach, it is assumed that there is no chemical interaction between pollutants, thus, in the initial stage, the prediction of NO_2 is made in terms of the NO_x level (Highways Agency, 1999). Then, the NO_x is converted to NO_2 via the above relationships based on empirical or chemical approaches. The NO_x/NO_2 relationship in the GRAM model follows these two approaches, and each approach is defined as either Option 1 or Option 2 respectively.

5.4.1 NO_x and NO_2 relationship in the empirical approach

The empirical equation, or the Option 1 in the GRAM model, is based on the Derwent-Middleton curve (Fisher, 1999b). The equation is as shown in equation (1).

$$NO_2 = 7.2769 + 2736NO_x + (5.10366*10^{-4})NO_x^2 + (4.4561*10^{-7})NO_x^3 \quad (1)$$

This relationship was developed from a data set obtained from an air quality monitoring site in central London (Fisher, 1999b). The NO_x/NO_2 relationship, which derives from an empirical equation, seems to be different from place to place, because it is formulated from conditions at one location. Therefore the relationship of NO_x/NO_2 in Bangkok was assumed to be different to that in London.

The relationship between the annual means of NO_x and NO_2 in Bangkok was studied from the hourly data between 1997 and 1999 at three roadside stations and seven general (urban background) stations located in Bangkok. The data were analysed for the linear and non-linear regression relationships in the unit of $\mu g/m^3$ and ppb. The R-squared (R^2) coefficient, or correlation, displays the agreement between the relationships and the measurements. The root mean square difference (RMSD) shows the performance of the prediction. The NO_2 estimated from the Bangkok empirical relationship (new NO_2) and London empirical relationship (old NO_2) were plotted against the measurements so as to compare their similarity .

The linear relationship of NO_x/NO_2 in Bangkok, and their R-square (R^2) are displayed in Table 5.6 and illustrated in Figures 5.1 – 5.2. The root mean square difference (RMSD) in Table 5.6 shows that the performances of the linear and non-linear approaches are similar. The non-linear equation in units of ppb was selected to test the prediction against the measurements. The measurements and predictions of the old NO_2 and new NO_2 are plotted in Figure 5.3.

Table 5.6 Relationship between NO_x and NO_2 in Bangkok

Type of relationship	unit	Relationship	R^2	RMSD
Linear relationship	$\mu g/m^3$	$NO_2 = 0.1743x + 27.451$	0.9185	±5.0
	ppb	$NO_2 = 0.1743x + 14.410$	0.9185	±2.6
Non-linear relationship	$\mu g/m^3$	$NO_2 = 27.092Ln(x) - 76.451$	0.9161	±5.1
	ppb	$NO_2 = 14.222Ln(x) - 30.966$	0.9161	±2.7

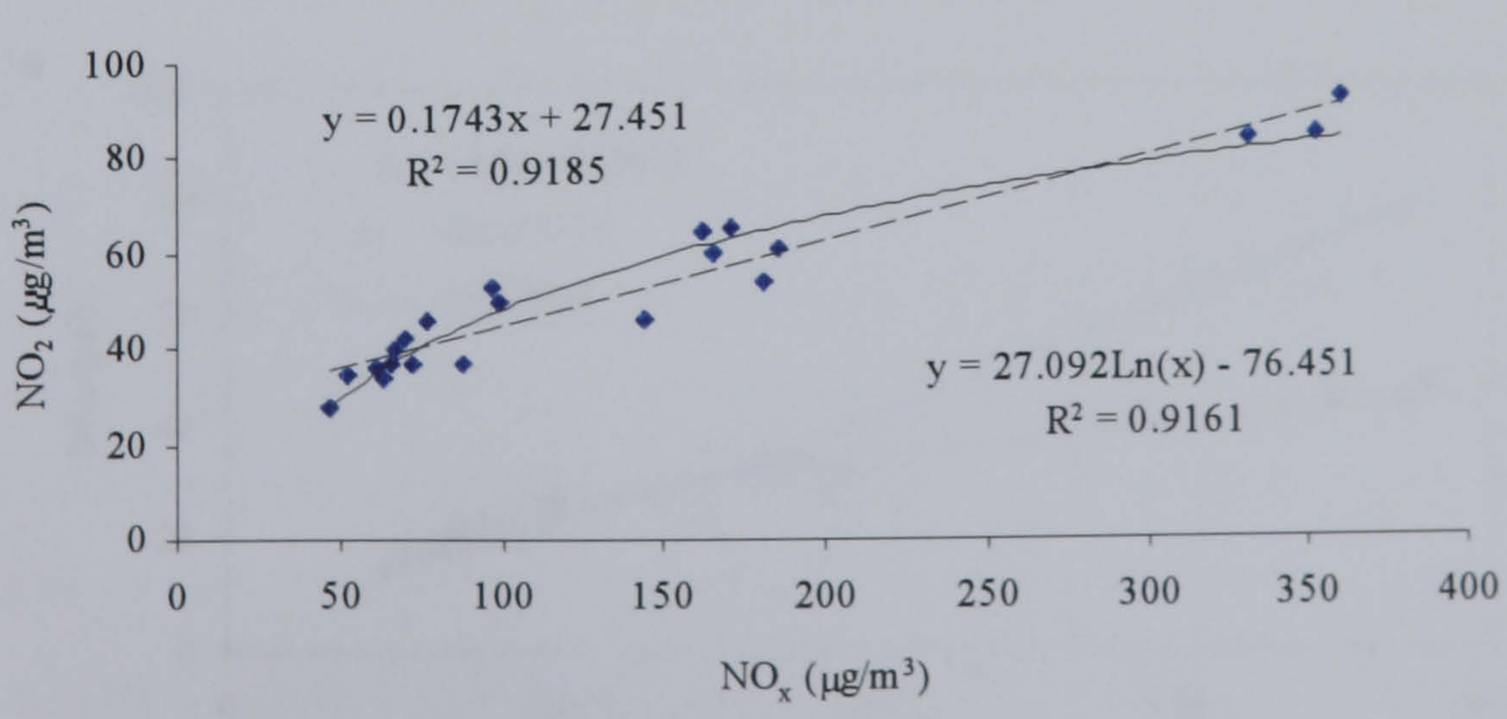


Figure 5.1 Relationship between NO_x and NO_2 in Bangkok when units in $\mu g/m^3$ is applied

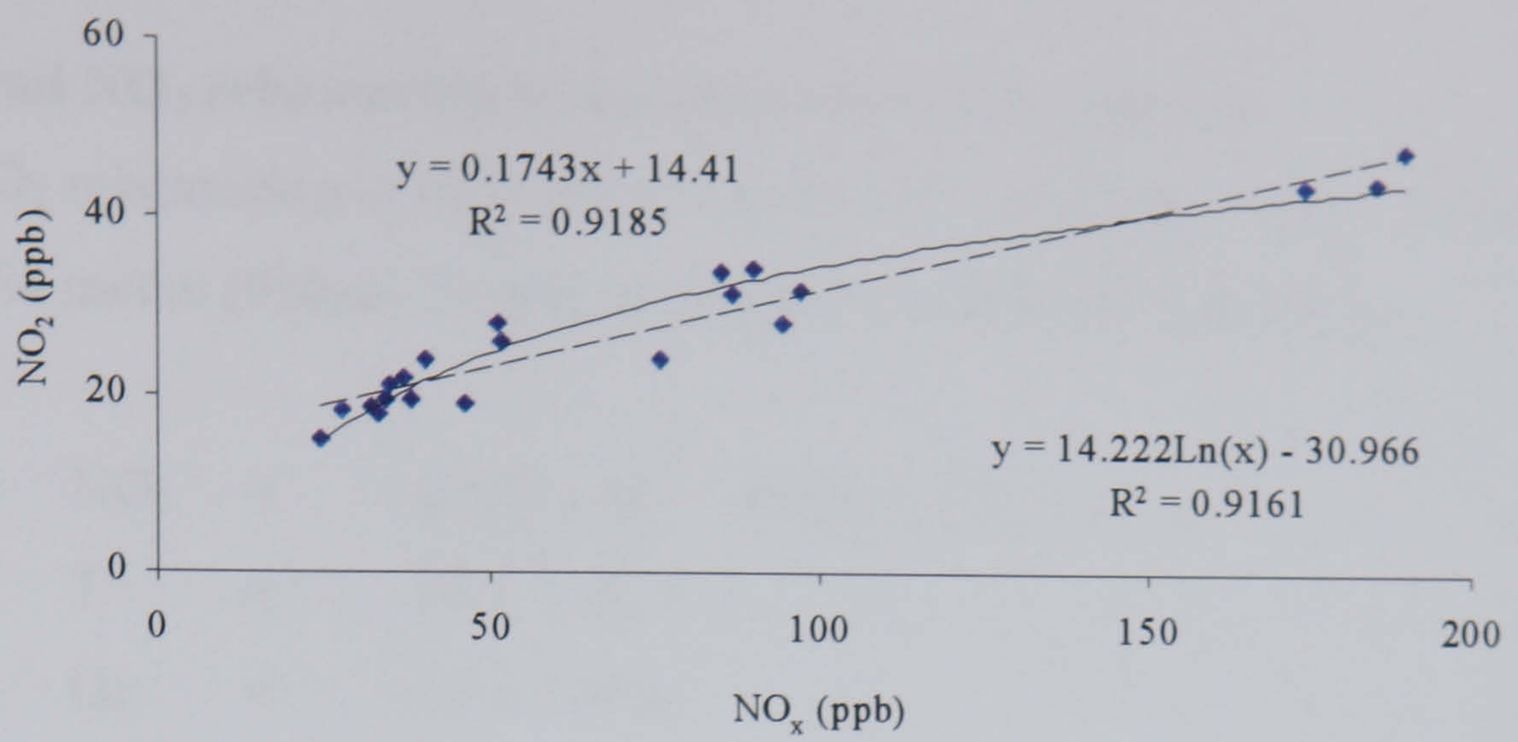


Figure 5.2 Realtionship between NO_x and NO_2 in Bangkok when units in ppb is applied

The high R-squared (R^2 >0.9) values obtained from both the linear and non-linear equations suggest that good performance would obtain if either of these equations are employed for predicting NO_2 from NO_x. The root mean square different (RMSD) in Table 5.6 also reveals the similarity in the performance between the linear and non-linear equations. The plot in Figure 5.3 shows that the old NO_2 prediction gives a much higher NO_2 level than the observed NO_2 when NO_x is greater than 100 ppb. Hence, the empirical relationship between NO_2 and NO_x in the GRAM model should be changed. Although, the R^2 and root mean square difference (RMSD) in the linear equation are similar to those in the non-linear equations, the non-linear equation was chosen because at the higher NO_x level as illustrated in Figures 5.1 and 5.2, the linear equation seems to go out of the range of the observations. Thus, the relationship of NO_2 and NO_x was changed from the equation (1) to equations (2) or (3) as the following.

$$NO_2 = 14.222\text{Ln}(x) - 30.966 \quad \text{ppb} \qquad (2)$$

$$NO_2 = 227.092\text{Ln}(x) - 76.451 \quad \mu g/m^3 \qquad (3)$$

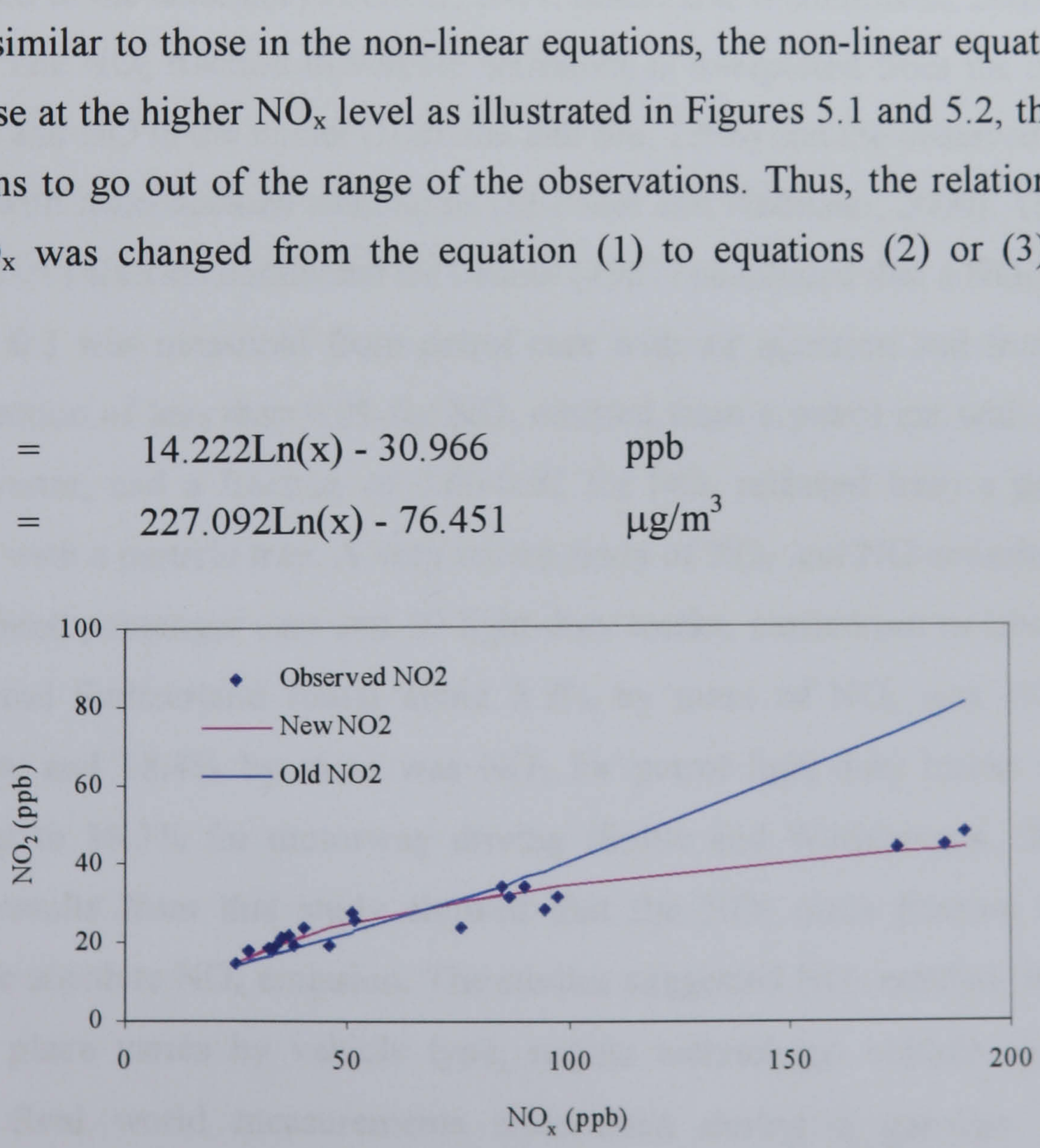


Figure 5.3 Comparison of the annual NO_2: observations against predictions of the new and old NO_2 equations

5.4.2 NO_x and NO_2 relationship in the photochemical approach

The NO_x/NO_2 relationship or the Option 2 in the GRAM model, which is also used in the CALINE4 model (Fisher, 2000d), is based on the following equation:

$$NO_2 = 0.5(T - (T^2 - 4NO_xO_x)^{0.5}) \quad (1)$$

where $T = NO_x + O_x + Z$ (2)

$$O_x = 20 + a\,NO_x \quad (3)$$

This section concerns the relationship in equation (3) where the 'O_x' means the O_3 + NO_2. The model defines 20 ppb as the background level for the application in the UK, and 'a' is the fraction of primary NO_2 emitted from mobile sources, which is defined to be 0.05 for prediction in the UK. The background O_3 and the fraction of primary NO_2 in Bangkok were assumed to be different to the values used in the GRAM model.

5.4.2.1 Fraction of primary NO_2 from mobile source

The primary NO_2 from vehicle emissions as a NO_2/NO_x ratio, or fraction, was recently studied in the laboratory (Lenner, 1987; Soltic and Weilenmann, 2003) and in road tunnels. The NO_2 fraction in vehicle emissions is interpreted from the observed levels of NO_2 and NO in the tunnel (Harrison and Shi, 1996) and the observed level in combination with mass balance techniques (El-Fadel and Hashisho, 2000). The study on NO_2/NO_x (v/v) fraction conducted by Lenner (1987) concluded that a NO_2 fraction of more than 0.3 was measured from petrol cars with air injection and from diesel vehicles, a fraction of less than 0.01 for NO_x emitted from a petrol car with a 3-way catalytic converter, and a fraction of 0.00-0.02 for NO_x released from a passenger diesel vehicle with a particle trap. A very recent study of NO_2 and NO emissions from six petrol-engined passenger cars and 10 light-duty trucks, carried out in laboratories in Germany and Switzerland found about 5.3% by mass of NO_x was NO_2 from passenger cars, and 18.4% by mass was NO_2 for petrol light-duty trucks and this figure goes up to 38.3% for motorway driving (Soltic and Weilenmann, 2003). In addition the results from this study showed that the NO_2 mass fraction depends strongly on the absolute NO_x emission. The studies suggested NO_2 emitted from road vehicles at a place varies by vehicle type, engine technology, vehicle speed and maintenance. Real world measurements undertaken during a gasoline vehicle-dominated period in the Queensway tunnel located in Birmingham, UK (Harrison and

Shi, 1996) found that the NO_2 fraction varied on a daily basis over three sampling days. The range of the NO_2 fraction was to be 0.03–0.055 on one weekend, and the ranges of 0.04-0.06 and 0.05-0.075 occurred on two weekdays. In practice, a widespread assumption of NO_2 fraction was employed. For example the fraction of 0.01 was applied for the 2007 emission inventory development in Dallas/Ford Worth Area, Texas (Kite, 2004), and the fraction of 0.15 was used in studying vehicle emission factors in the Salim Salam tunnel, Beirut (El-Fadel and Hashisho, 2000).

The measurements of NO_x emissions in the form of NO_2 from vehicles, in laboratory and the measurement in road tunnels have not been conducted in Thailand. The fraction of primary NO_2 from mobile sources in this research was obtained indirectly from the observed NO_x and NO_2 levels at roadside and urban background sites during the morning peak (06.00-08.00 am) and the prior morning peak (01.00-05.00 am). The duration of the morning peak was chosen in order to avoid major secondary NO_2 production from the photochemical reaction between NO_x and the O_3 level during the daytime. In Bangkok, the O_3 level at the roadside sites during the prior morning peak was very low (approximately 2-5 ppb), when compared to NO_2 and NO_x. Thus it was neglected.

The hourly observed NO_2 and NO_x concentrations between 1997 and 1999 were used. The roadside stations and their paired stations at urban background sites for this purpose were: Dindaeng-Ramkhumhaeng, Ladphrao-Klong Jun, and Thonburi Electricity-Nonsi. In the previous chapter, the site paired with the Thonburi Electricity roadside station was Singharach station. However it was changed to the Nonsi station due to the impact of traffic on local roads near to the station. Initially the hourly data in a year were analyzed for the annual hourly variation of NO_2 and NO_x levels between 01.00 and 08.00 hours. The prior peak and morning peak concentrations at each station were calculated. The NO_x and NO_2 levels originated from all sources during the morning peak at roadside and urban background sites were analyzed for the differences between the levels during the morning and prior peaks. At the urban background location, the NO_x and NO_2 levels were from all sources other than road vehicles. While NO_x and NO_2 levels at roadside sites during the morning peak were from both road vehicles and the other sources in the urban background area. The levels of NO_x and NO_2 emitted directly from road vehicles were calculated from the

difference in levels found at these two locations. Then, the fraction of NO_2/NO_x emitted from road vehicles at roadside sites were obtained. The fractions of primary NO_2 from mobile source at all roadside sites were averaged to obtain a representative value for Bangkok.

The levels of NO_2 and NO_x from all sources at all stations are shown in Table 5.7. After subtracting the levels of NO_2 and NO_x emitted from all sources at urban background stations, as shown in Table 5.8, it was found that the primary NO_2 from vehicle emission at roadside areas was in a range of 0.07 – 0.31, as seen in Table 5.9, with a fraction of 0.16 on average. It can be seen that NO_2 fractions varied from place to place and at the same place they also varied year by year. The results agree with the Solitic and Weilenman's work (2003) on the variation of NO_2 fraction at places and Harrison and Shi's finding (1996) on the variation according to different times. It can be concluded that the NO_2 fraction is dependent on the conditions of vehicles travelling on a specific road at a specific time.

The results show that the fraction of primary NO_2 from vehicle emissions in Bangkok of 0.07 – 0.31, with 0.16 on average, is much greater than that found in Birmingham, UK, which was 0.03 – 0.08, and the value of 0.05 employed in the GRAM model. However, the range of NO_2 fraction found from this research is similar to that of Soltic and Weilenmann works (2003), and the average NO_2 fraction close to the fraction used in El-Fadel and Hashisho study (2000). For the development of the Bangkok GRAM, this research proposes the value of 0.16 for the primary NO_2 from vehicle emissions in the base year of 1998.

Table 5.7 NO_2 and NO_x levels at roadside sites in Bangkok unit: ppb

Dindaeng						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
01.00	33.90	163.53	30.17	157.01	28.61	179.67
02.00	31.00	149.77	28.49	153.66	27.08	164.30
03.00	29.54	141.07	26.53	144.61	24.77	162.93
04.00	28.92	141.82	26.08	143.24	25.34	153.17
05.00	30.88	160.98	29.26	174.70	35.66	153.58
06.00	39.80	242.81	38.98	248.05	40.87	219.43
07.00	50.51	330.46	45.52	294.37	45.57	213.14
08.00	53.56	316.52	49.83	280.86	50.92	231.74
Prior peak level	30.85	151.43	28.10	154.64	28.29	162.73
Morning peak level	47.96	296.59	44.78	274.43	45.79	221.44
Level of all sources	17.11	145.16	16.67	119.78	17.50	58.71
Ladphrao						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
01.00	25.96	85.31	15.49	56.92	19.58	81.31
02.00	23.67	75.27	14.07	49.55	18.55	71.97
03.00	22.31	72.09	13.01	44.87	18.01	69.87
04.00	21.24	73.14	13.18	52.98	18.49	73.71
05.00	21.57	84.95	14.09	65.70	20.65	83.31
06.00	23.66	111.04	16.45	93.73	23.83	109.25
07.00	25.57	124.83	18.60	107.40	25.91	136.85
08.00	27.99	111.68	20.92	96.87	29.77	116.31
Prior peak level	22.95	78.15	13.97	54.00	19.06	76.04
Morning peak level	25.74	115.85	18.66	99.33	26.51	120.80
Level of all sources	2.79	37.70	4.69	45.33	7.45	44.77
Thonburi Electricity						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
01.00	28.50	77.76	25.62	70.96	25.98	74.00
02.00	25.83	69.10	23.28	62.86	22.76	64.34
03.00	24.65	65.82	21.55	58.95	22.52	56.50
04.00	24.29	67.27	20.66	59.30	22.07	59.81
05.00	25.28	77.00	21.53	67.89	23.75	65.66
06.00	27.86	108.27	24.27	94.79	28.31	94.58
07.00	31.11	128.64	28.24	119.12	33.39	126.65
08.00	35.64	121.13	33.86	121.50	38.95	122.27
Prior peak level	25.71	71.39	22.53	63.99	23.42	64.06
Morning peak level	31.54	119.34	28.79	111.80	33.55	114.50
Level of all sources	5.83	47.95	6.26	47.81	10.13	50.44

Table 5.8 NO_2 and NO_x levels at urban background sites in Bangkok unit: ppb

Ramkhumhaeng						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
01.00	22.05	42.02	20.66	35.60	18.08	42.23
02.00	20.47	37.83	18.55	31.16	16.28	39.43
03.00	19.78	36.39	17.32	28.04	15.08	35.77
04.00	18.89	34.74	16.38	26.99	14.61	34.46
05.00	18.35	33.38	15.50	25.31	15.17	33.99
06.00	18.82	39.10	17.08	31.04	16.73	38.91
07.00	20.21	52.17	19.14	42.96	18.30	49.14
08.00	21.95	51.97	21.74	50.32	19.35	51.08
Prior peak level	19.91	36.87	17.68	29.42	15.84	37.18
Morning peak level	20.33	47.74	19.32	41.44	18.13	46.38
Level of all sources	0.42	10.87	1.64	12.02	2.28	9.20
Klong Jun						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
01.00	23.36	44.56	20.09	40.55	17.14	42.12
02.00	21.60	40.31	17.89	36.20	15.24	40.11
03.00	20.20	36.99	16.39	33.27	14.64	38.96
04.00	19.58	36.54	16.14	33.27	14.21	39.83
05.00	19.55	38.92	16.29	35.63	14.76	42.49
06.00	21.06	51.52	17.86	47.45	16.58	51.55
07.00	22.26	64.70	19.53	62.34	19.72	65.10
08.00	23.40	53.46	21.20	53.92	19.98	60.01
Prior peak level	20.86	39.47	17.36	35.78	15.20	40.70
Morning peak level	22.24	56.56	19.53	54.57	18.76	58.89
Level of all sources	1.38	17.09	2.17	18.79	3.56	18.18
Nonsi						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
01.00	23.26	47.60	15.15	40.51	3.44	56.27
02.00	21.40	43.70	13.71	35.38	3.91	49.50
03.00	19.95	39.88	12.98	34.84	4.02	40.68
04.00	19.56	40.77	13.08	37.43	3.65	38.99
05.00	20.58	48.75	13.99	45.48	3.24	41.36
06.00	21.56	62.28	15.21	58.48	2.60	48.38
07.00	22.37	77.74	17.15	75.38	3.77	61.03
08.00	25.47	75.05	20.97	66.98	8.15	66.32
Prior peak level	20.95	44.14	13.78	38.73	3.65	45.36
Morning peak level	23.13	71.69	17.78	66.95	4.84	58.58
Level of all sources	2.18	27.55	4.00	28.22	1.19	13.22

Table 5.9 NO_2 fraction from vehicle emissions in Bangkok unit: ppb

Dindaeng - Ramkhumhaeng						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
Level of all sources at roadside	17.11	145.16	16.67	119.78	17.50	58.71
Level of all sources at urban background	0.42	10.87	1.64	12.02	2.28	9.20
Level of mobile source	16.69	134.29	15.03	107.76	15.21	49.51
NO_2 fraction of mobile source	0.12		0.14		0.31	
Ladphrao - Klong Jun						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
Level of all sources at roadside	2.79	37.70	4.69	45.33	7.45	44.77
Level of all sources at urban background	1.38	17.09	2.17	18.79	3.56	18.18
Level of mobile source	1.41	20.61	2.52	26.54	3.89	26.58
NO_2 fraction of mobile source	0.07		0.09		0.15	
Thonburi Electricity - Nonsi						
Time	1997		1998		1999	
	NO_2	NO_x	NO_2	NO_x	NO_2	NO_x
Level of all sources at roadside	5.83	47.95	6.26	47.81	10.13	50.44
Level of all sources at urban background	2.18	27.55	4.00	28.22	1.19	13.22
Level of mobile source	3.65	20.40	2.26	19.59	8.94	37.22
NO_2 fraction of mobile source	0.18		0.12		0.24	

5.4.2.2 Background ozone

As mentioned previously the reaction between O_3 and NO is the main production route for NO_2. The O_3 used for the prediction of NO_2 in the GRAM model, is the level of background O_3 in the area. Naturally, O_3 at ground level is formed indirectly by the action of sunlight on NO_2 (DOH, 1998). In the morning, the increasing of emissions from traffic and other sources, and solar radiation produce more ozone. The peak of O_3 in general, occurs in the middle of the afternoon and the concentration decreases in the evening and at night, because there is no solar radiation to photolyse NO_2 (Colls, 1997). It is found that O_3 tends to build up downwind of urban conurbations, and can travel long distances. Peak levels tend to occur in rural areas (DOH, 1998). The observed annual mean O_3 in the urban centre areas, such as at London Bloomsbury, was 11, 10, and 10 ppb in 1995, 1997, and 1998 respectively (AEAT, 2001). The annual mean O_3 level of 6 ppb was observed at Marylebone Road, a road with very heavy traffic in 1997 and 1998. The observed annual mean O_3 in the urban background area, for example, at London Bexley was 18, 16, and 18 ppb in 1995, 1997, and 1998 respectively (AEAT, 2001). The default background O_3 level of 20 ppb was used in the GRAM model. It is a bit higher than the annual mean level.

The observed hourly O_3 level in Bangkok between 1997 and 1999 was studied to determine its range (minimum and maximum), the diurnal variation and the annual mean. The data were collected from three roadside and four urban background air quality monitoring stations The diurnal variation of each station was averaged and a plot made of the average annual diurnal variation of O_3 in Bangkok between 1997-1999, so as to illustrate the profile of O_3 level at places in Bangkok. Photochemical reactions occur during the daytime, hence the O_3 level during the daytime (06.00 – 18.00 hours) was assumed to be involved in the reaction. Hence, the O_3 level at the roadside and urban background areas during 06.00 – 18.00 hours was considered to be its range and average, so as to obtain representative background O_3 levels for Bangkok.

The observed O_3 at the roadside and urban background air quality monitoring stations during 1997 – 1999 are shown in Table 5.10. The annual diurnal variations of O_3 over the whole period are shown in Table 5.11 and Figure 5.4. As expected the maximum and annual O_3 levels at urban background areas were greater than the levels at roadside areas. The annual means were about 4 - 10 ppb at the roadside sites and 10 - 23 ppb at urban background areas. These ranges are similar to the observations in London. Figure 5.4 illustrates low levels of O_3 during the night-time and abundant O_3 during the daytime. The O_3 level during the daytime (06.00 – 18.00 hour), the time when the photochemical reaction take place, at the roadside and urban background areas as seen from Table 5.11, ranged between 7.0 – 29.1 ppb and 18.2 ppb in average. Because of the similarity of the annual mean O_3 found in London and Bangkok, the average of 18 ppb was calculated from O_3 levels at roadside and background sites, and this value will apply to estimates in both areas, the original 20 ppb was kept in the new Bangkok model.

Table 5.10 O_3 level in the areas of roadside and urban background during 1997 - 1999

Station	1997		1998		1999	
	Range	Annual mean	Range	Annual mean	Range	Annual mean
Roadside station						
Dindaeng	0-83.0	4.9	0-84.0	5.0	0-73.0	3.7
Ladphrao	0-114.0	8.8	0-112.0	9.6	0-79.0	8.7
Thonburi Electricity	0-97.0	9.1	0-101.0	9.3	0-67.0	9.3
Urban background station						
Klong Jun	0-124.0	15.7	0-191.0	16.7	0-141.0	16.6
Nonsi	0-141.0	10.7	0-136.0	9.7	0-109.0	11.1
Ramkhumhaeng	0-148.0	16.6	0-177.0	20.1	0-152.0	23.1
Singarach	0-181.0	17.3	0-154.0	19.3	0-115.0	13.6

Unit: ppb

Table 5.11 Annual diurnal variation of O_3 during 1997-1999

Time	Roadside station			Urban background			
	Dindaeng	Ladphrao	Thonburi E.	Nonsi	Ramkhumh.	Singharach	Klong Jun
01.00	1.59	3.27	4.30	3.56	7.88	7.93	4.67
02.00	1.74	3.41	4.71	3.63	8.20	7.73	4.69
03.00	1.75	3.44	4.26	3.72	8.08	7.47	4.61
04.00	1.63	3.26	3.93	3.28	7.78	6.91	4.45
05.00	1.60	2.99	3.48	2.69	7.28	6.32	3.72
06.00	1.64	2.82	2.80	2.08	6.36	5.28	2.79
07.00	2.22	3.10	3.08	2.58	6.54	5.57	2.84
08.00	2.69	4.18	4.88	5.45	9.68	8.10	5.95
09.00	3.72	7.35	8.19	10.88	17.26	14.68	13.24
10.00	5.68	12.44	13.32	18.01	28.19	22.73	23.78
11.00	8.07	17.65	19.17	23.88	38.90	29.96	33.40
12.00	10.12	21.88	21.95	27.48	44.52	34.12	38.94
13.00	11.47	23.54	23.12	27.96	46.37	34.93	40.82
14.00	12.10	23.12	22.42	26.29	45.33	34.23	40.33
15.00	11.36	21.63	20.68	23.41	43.16	33.48	37.60
16.00	10.01	18.73	18.10	19.34	38.57	30.97	33.41
17.00	7.37	14.79	14.16	13.61	31.57	26.79	25.78
18.00	4.98	9.74	10.10	8.29	21.86	20.79	16.45
19.00	3.19	5.53	6.06	5.46	13.31	14.21	8.06
20.00	2.41	3.85	4.53	4.07	9.61	10.52	5.26
21.00	2.10	3.36	3.70	3.35	8.06	9.10	4.27
22.00	1.66	3.05	3.35	2.82	7.37	8.28	3.94
23.00	1.46	2.88	3.68	2.93	7.27	8.09	4.00
24.00	1.50	3.02	3.93	3.26	7.50	8.06	4.17
Average O_3 (06.00 -18.00 hr)	7.03	13.92	14.00	16.10	29.10	23.20	24.26

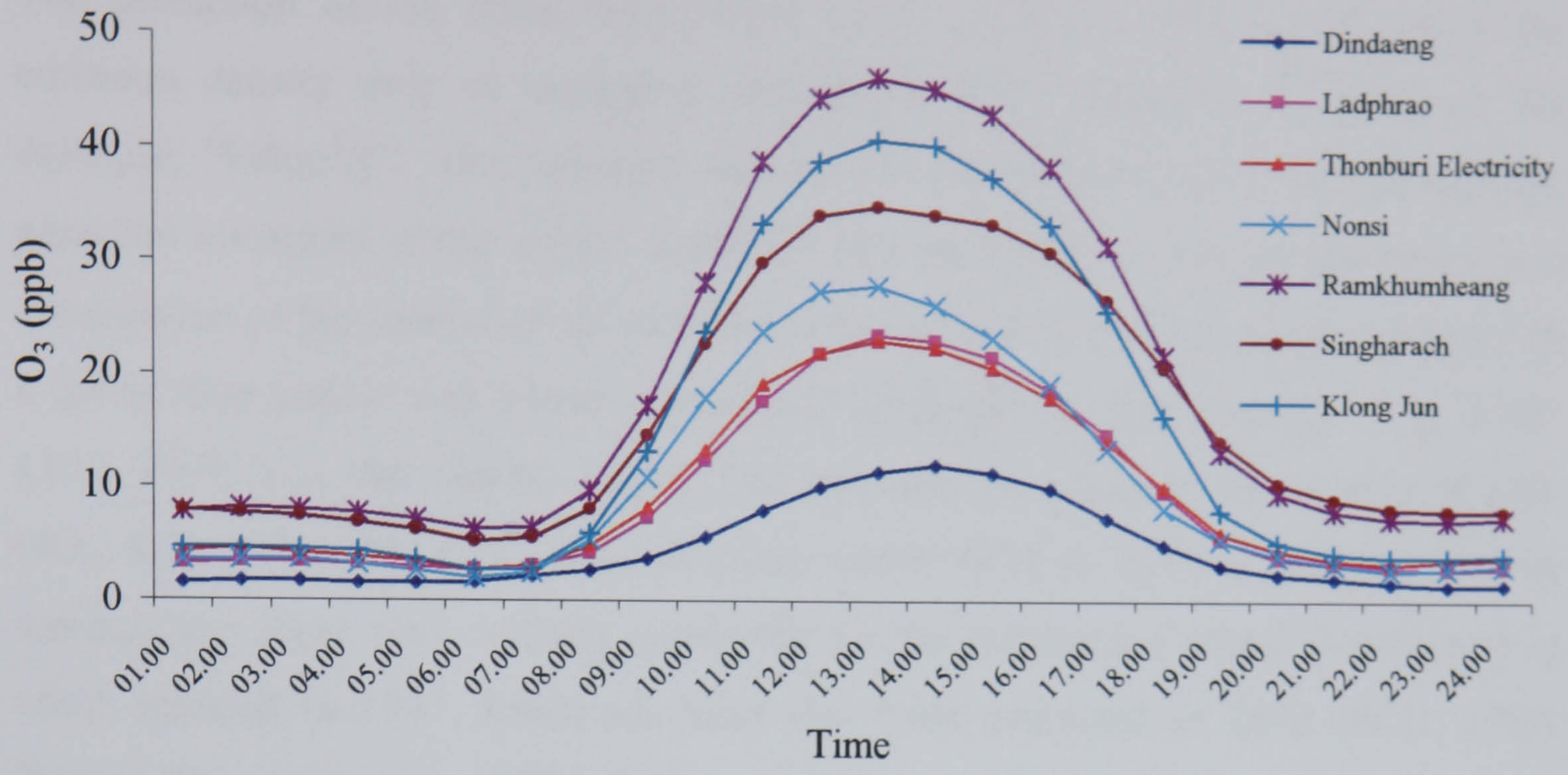


Figure 5.4 Annual diurnal variation of O_3 in Bangkok during 1997-1999

In combination with the fraction of NO_2 and ambient temperature from previous sections, the prediction of NO_2 using the Option 2 was adjusted. In part of the O_3 calculation the new equation is the following:

$$O_x = 20 + 0.16NO_x$$

Figure 5.5 shows the comparison between the observed NO_2 and predictions of the new NO_2 and the old NO_2 formulations in the Option 2. A better agreement with the new NO_2 method than the old one is obviously seen from the figure, especially at high NO_x levels.

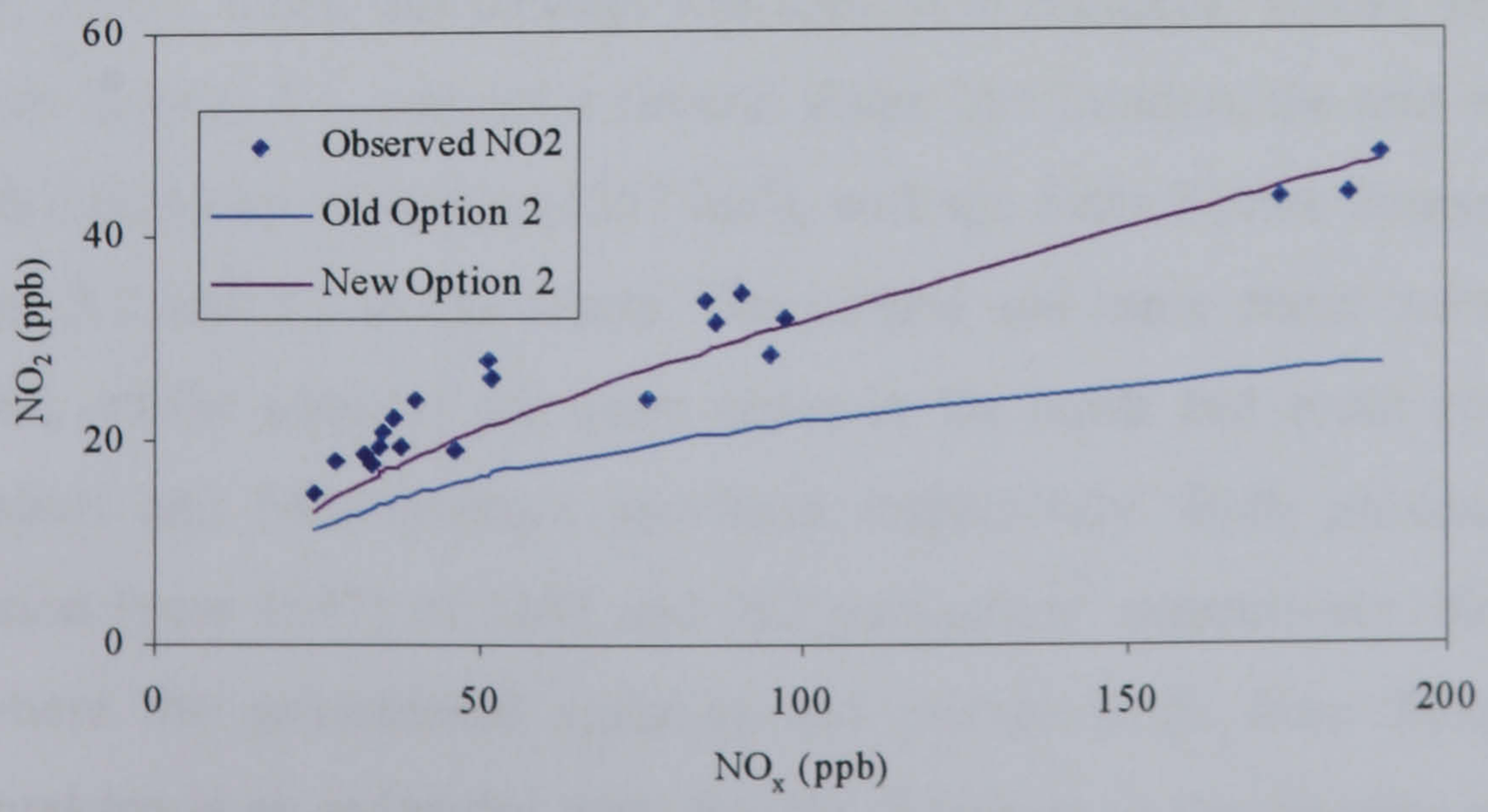


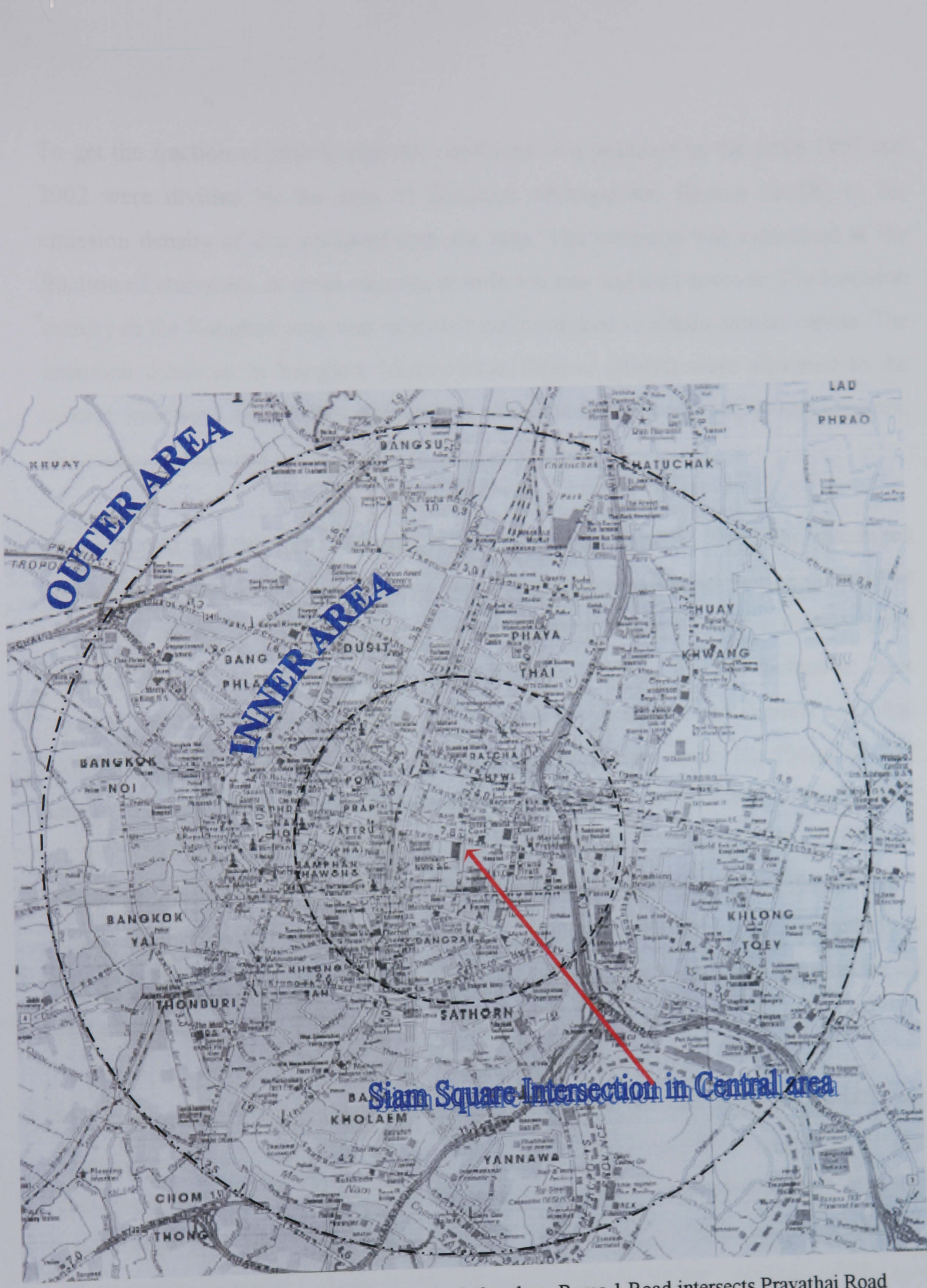
Figure 5.5 Comparison between observed NO_2 and predictions in Bangkok during 1997-1999

5.5 Emission density and fraction of mobile source

The prediction of the urban background levels in the GRAM model needs the emission density over an integrated area as an input parameter, in units of, for example, "kt/km^2/y". The emission density can be obtained from the atmospheric emission inventory of the area in question. The atmospheric emission inventory is a compilation of the amount of air pollution from all sources entering the atmosphere in a given time period and within a particular geographical area (Boubel et al, 1995; LRC, 1997; Liu and Liptak, 2000). The atmospheric emission inventories of CO, NO_x, SO_2, HC, VOC, CH_4, and particulate matter (PM as TSP) in Bangkok and its surrounding areas were initially conducted by the Pollution Control Department in 1992, updated in 1997. Emissions have also been estimated in 2002 (PCD, 1994, 2000). The study area, 7723 km^2 in total, covered six provinces of Bangkok, Samutprakarn, Nonthaburi, Phrathumthani, Nakornprathom, and Samutsakorn, hereinafter called the Bangkok Metropolitan Region (BMR). It includes a population of 8.6 million in 1992, and 9.1 million in 1997 (PCD, 1994, 2000). The emission sources and density over the Bangkok area (1569 km^2) were extracted and modified for the purposes of this research.

The GRAM model assumes an urban area as a circular shape, dividing it into central, inner, and outer zones. The zone division follows the DETR's criteria (DETR, 1998c). Central zone is the area in a diameter of 6.5 km from the centre point of urban area. Inner zone covers between diameter scale of 13 km and 16 km. Outer zone is beyond diameter scale of 16 km until 40 km. The emission density over the central and inner zones is assumed as about 3 and 2 times respectively of the density of the outer zone (Fisher, 2003). When this concept was applied to Bangkok, whose shape is irregular as shown in Map 5.1, and not a circular shape like London, the area of Bangkok was set with a diameter of 40 km (1257 km^2), with the Siam Square Intersection as shown in Maps 5.1 and 5.2 as the centre. The central and inner zones were in the area of Bangkok, whilst some of the outer zones in the north and south covered a part of Nonthaburi and Samutprakarn provinces respectively. Both provinces have dense population (year 1997) of 1287 and 952 person/km^2 respectively. Nonthaburi is the area where the government agencies and private firms from Bangkok move to. Samutprakarn is an industrial area. So, the activities in the circular area sited out of the Bangkok political area were assumed to be similar to those in Bangkok area.

Map 5.1 Map of Bangkok and its centre point



Map 5.2 Siam Square, centre point of Bangkok, where Rama 1 Road intersects Prayathai Road

To get the fraction of mobile sources, emissions of a pollutant in the years 1997 and 2002 were divided by the area of Bangkok Metropolitan Region (BMR) to the emission density of that pollutant over the area. The emission was calculated as the fraction of emissions as point sources, mobile sources and area sources. The emission density in the Bangkok area was extracted and complied to obtain similar results. The emission densities in Bangkok Metropolitan Region (BMR) were allocated to the central, inner and outer zones of Bangkok using the GRAM concept. In this research, the emission densities of NO_x and PM were of interest.

Because PM in the PCD inventory had been expressed as the total suspended particulate matter (TSP), a conversion factor from previous studies was applied to PM to obtain the PM_{10} emission density. A study conducted by Sirisawat (1992) found that the PM_{10} and TSP measured by the Gravimetric High Volume method at three sampling sites in Bangkok during a rainy season between June and October 1992 had a fraction of 0.66. In 1998, the same method was used for observing PM_{10} and TSP during the northeast monsoon (winter season) and southwest monsoon (rainy season) at four sites in Bangkok and the fraction of PM_{10} was 0.582 (Chotipong, 1998). A PM_{10} fraction of 0.588 in Bangkok was also found in 2000 (Kaew-Ngarm, 2000). Thus a fraction of 0.6 was assumed and applied to obtain the PM_{10} emission density in the Bangkok Metropolitan Region (BMR) and the same fractions applied to all emission sources.

The emissions from sources in the Bangkok Metropolitan Region (BMR) and Bangkok in 1997 and 2002 are shown in Tables 5.12 and 5.13 respectively. The emissions of CO, HC, and CH_4 in the Bangkok Metropolitan Region (BMR) showed a small increase in 2002 as expected, whilst the remaining pollutants decreased slightly. The development of the Bangkok GRAM model focused on the emissions of NO_x and PM from mobile sources. Around 80 and 54 percent of NO_x, and particulate matter (PM) in Bangkok Metropolitan Region (BMR) during those years originated from mobile source, whilst more than 90% of these pollutants in Bangkok were emitted from mobile sources.

Table 5.12 Emission from sources in BMR (7723 km^2) in 1997 and 2002

Source	Unit	NO_x	SO_2	CO	HC	VOC	CH_4	PM	PM_{10}
Year 1997									
Total emission	t/y	329161[a]	240016[a]	463775[a]	232937[a]	26036[a]	177370[a]	38192[a]	22915
Emission density	$kt/km^2/y$	0.0426	0.0311	0.0601	0.0302	0.0034	0.0230	0.0049	0.0030
Point source	%	17	95.8	1.4	N/A	7.7	N/A	9.8	9.8
Mobile source	%	80.4	4.2	75.4	100.0	N/A	N/A	53.9	53.9
Area source	%	2.6	0.1	23.2	N/A	92.3	100	36.3	36.3
Year 2002									
Total emission	t/y	305641[a]	211009[a]	501233[a]	272670[a]	25820[a]	185653[a]	36705[a]	22024
Emission density	$kt/km^2/y$	0.0396	0.0273	0.0649	0.0353	0.0033	0.0240	0.0048	0.0029
Point source	%	16.0	95	1.1	N/A	6.8	N/A	8.8	8.8
Mobile source	%	81.0	4.9	77.4	100.0	N/A	N/A	53.8	53.8
Area source	%	3.0	0.1	21.5	N/A	93.2	100.0	37.4	37.4

Source: (a) PCD (2000)

N/A = not available

Table 5.13 Emission from sources in Bangkok (1569 km^2) in 1997 and 2002

Source	Unit	NO_x	SO_2	CO	HC	VOC	CH_4	PM	PM_{10}
Year 1997									
Total emission	t/y	177724[a]	31315[a]	254696[a]	171098[a]	1361[a]	100436[a]	14245[a]	8547
Emission density	$kt/km^2/y$	0.1133	0.0200	0.1623	0.1090	0.0009	0.0640	0.0091	0.0054
Point source	%	3.7	78.0	0.4	N/A	28.0	N/A	5.7	5.7
Mobile source	%	92.7	22.0	97.9	100.0	N/A	N/A	93.2	93.2
Area source	%	3.6	0.0	1.8	N/A	72.0	100.0	1.1	1.1
Year 2002									
Total emission	t/y	183654[a]	28916[a]	292740[a]	203276[a]	1583[a]	105126[a]	14818[a]	8891
Emission density	$kt/km^2/y$	0.11705	0.01843	0.18658	0.129557	0.0101	0.067	0.0094	0.0057
Point source	%	3.1	73.6	0.3	N/A	21.0	N/A	4.7	4.7
Mobile source	%	93.1	26.4	97.8	100.0	N/A	N/A	94.2	94.2
Area source	%	3.8	0.0	1.9	N/A	79.0	100.0	1.1	1.1

Source: (a) PCD (2000)

N/A = not available

Because of similar emission densities in 1997 and 2002, the values of 0.04 and 0.003 $kt/km^2/y$ were assigned to the NO_x and PM_{10} emission densities respectively in the Bangkok Metropolitan Region (BMR) and the figures of 0.12 and 0.006 $kt/km^2/y$ were for the NO_x and PM_{10} emission densities respectively in Bangkok. The figures were used to estimate the density in zones according to the GRAM model concept. The NO_x densities in Bangkok were around 3 times greater than the density in the Bangkok Metropolitan Region (BMR). Thus it was simple to extrapolate NO_x densities of 0.12, 0.08, and 0.04 $kt/km^2/y$ for the central, inner and outer zones of Bangkok respectively. The inventory showed that the PM density in the Bangkok Metropolitan Region (BMR) was just a half of that in Bangkok and the pattern of the

fraction of source contribution was different from that of NO_x. Outside of Bangkok, the mobile sources and area sources were the main PM sources, while in Bangkok, the PM mainly originated from the mobile sources. If the allocation of PM over the Bangkok area was based on the PM density in the Bangkok Metropolitan Region (BMR), the PM density over the Bangkok area would seem to be underestimated. Thus, PM density in the Bangkok area was based on PM over the Bangkok area only. Hence, the PM density was distributed for the central, inner and outer zones of Bangkok as 0.018, 0.012 and 0.006 kt/km^2/y respectively.

Similar to the trend in Bangkok, the atmospheric emission inventory conducted in the area of London out to the M25 (2466 km^2) in 1995, as shown in Table 5.14, points to road transport as the main source of NO_x, and PM_{10}, contributing emissions of around 75 and 77 percent respectively (LRC, 1997). Recently, Transport for London (TfL) produced an atmospheric emissions inventory for Greater London (Greater London Authority, 2004). The London Atmospheric Emissions Inventory (LAEI) was released in October 2003, and includes emissions data for 1999, 2001 and 2005. The emissions of NOx and PM_{10} in the Greater London inventory in 1999 and 2004/2005 are shown in Table 5.15. Due to the differences in the study areas, it is quite difficult to compare the emissions of the old and new inventories. For predicting pollutants in future years, the 1999-emission was chosen and assigned into emission densities in zones as shown in Table 5.16. Comparisons between the two cities show that NO_x densities in London were greater that of Bangkok, while the PM_{10} emission densities were lower.

Table 5.14 Emission from sources in London - M25 (2466 km^2) in 1995

Source	Unit	NO_x	SO_2	CO	CO_2	NMVOC	C_6H_6	1,3 butadiene	PM_{10}
Total emission	t/y	147581	24865	535902	34243	137385	3014	780	9844
Emission density	kt/km^2/y	0.0598	0.0101	0.2173	0.0139	0.0557	0.0012	0.0003	0.0040
Road transport	%	75.1	22.8	96.8	28.7	52.6	82.5	97.0	77.3
Other mobile	%	7.3	5.6	1.4	5	1.4	2.6	2.9	5.4
Stationary	%	17.6	71.6	1.8	66.3	46.0	14.9	0.0	17.3

Source: Modified from LRC (1997)

Table 5.15 Emissions of NO_x and PM_{10} in Greater London (1579 km^2)

NO_x [a]		1999	2005
Total emission	t/y	109664	82427
Emission density	$kt/km^2/y$	0.0695	0.0522
PM_{10} [b]		1999	2004
Total emission	t/y	4041	2996
Emission density	$kt/km^2/y$	0.0026	0.0019

Source: (a) Islington (2003)
(b) Carruthers, Blair and Johnson (2003)

Table 5.16 Emission density in London and Bangkok (unit: $kt/km^2/y$)

Zone	NO_x	PM_{10}
London in 1999		
Central	0.21	0.009
Inner	0.14	0.006
Outer	0.07	0.003
Bangkok between 1997-2002		
Central	0.12	0.018
Inner	0.08	0.012
Outer	0.04	0.006

5.6 Resuspended dust

The Gaussian dispersion approach estimates the particulate matter levels by simulating them from the emission rates, meteorological data and receptor location. The physical and chemical sources or sinks e.g. transformation, removal, and resuspension, are not included due to the assumption of a steady state system. Hence, the performance of the Gaussian-based models may decrease when it is applied to locations where a high level of resuspended dust exists. In urban areas, especially roadside sites, it was found from previous studies that the resuspended dust was one of the main sources of particulate matter. For example, in Santa Barbara County, California, USA, the resuspended dust near the roadside or the road dust, estimated by chemical mass balance (CMB) receptor modelling, accounted for 25%-27% of the observed PM_{10} at three urban sites during 1989 (Chow, Watson, Lowenthal, 1996). In North Carolina, a very recent study on the tailpipe, resuspended road dust, and break-wear emission factors from on-road vehicles found that 50%-100% of the PM_{10}

emission factor from the heavy-duty diesel (HDD) vehicles, and 40% - 98% of that from light-duty spark ignition (LDSI) vehicles was the resuspended road dust component (Abu-Allaban, et al, 2003). In Berlin, Germany, a study (Lenschow et al, 2001) on the PM source assumed that the difference of PM level between roadside and urban background stations was attributed to the road contribution. The road contribution was the combination of vehicle exhaust, tyre abrasion, and road dust. The proportion by emission source was applied to the chemical components of the observed PM_{10}. The study found that the roadside PM_{10} was about 40% higher than the background level, and 45% of the additional PM_{10} was attributed to resuspended material, mainly soil. This means that 12.9% of PM_{10} near busy streets in Berlin was resuspended road dust. A study on metal emissions from road traffic conducted in two tunnels in Sweden, found that the concentrations of larger particles and of several metals were apparently dominated by resuspended matter rather than by emission from vehicles (Sternbeck, Sjodin, and Andreasson, 2002). In Spain, results observed at a kerbside site in the period 1999 - 2001 demonstrated that around 13.5% of the PM_{10} mass was made up of road dust, and 12% was attributed to carbonaceous particle from exhaust emission and tyre erosion (Alastuey, 2003).

In Asia, road dust is also a major contributor to the particle levels in the air. The resuspension of dust from paved roads was estimated by the chemical mass balance (CMB) method to be 15±6% and 7±6% of the PM_{10} in urban and suburbs respectively in metropolitan Kaohsiung, the biggest industrial city in southern Taiwan (Yuan, Lee, and Liu, 2000). In Mumbai, India, a multivariate analysis (VA) technique, factor analysis-multiple regression (FA-MR) (a receptor modeling technique), was used for quantitative apportionment of the sources contributing to the suspended particulate matter (SPM) at two traffic junctions. The model indicated that road dust contributed up to 41%. Hence, it is clearly seen that resuspended dust is a large share of airborne particle level in urban areas and one gets a bigger fraction at roadside sites. However, its level varies from place to place. Thus the prediction of airborne particle concentration should take resuspended dust into account, and the level of resuspended dust at a location should be studied.

The study of the source apportionment of particulate matter is based on the technique of receptor modelling. Receptor modelling is the term applied to the use of measurements of air pollutant (in this case particles) in the atmosphere (rather than on source strength) to estimate quantitatively the contributions of different source categories to the mass of particles and of particular chemical components (APEG, 1999). The studies in the research literature mentioned above were mainly based on two techniques: the chemical mass balance method (CBM), and the use of one or more of the multivariate methods. The chemical mass balance (CBM) model requires the levels of chemical components and their fraction in source emissions (the source profile) and data on the chemical composition of particles at the receptor to solve the mass balance equation (QUARG, 1996; Hueglin et al, 2000). The chemical mass balance (CBM) method performs reasonably well with primary emissions, but poorly when it is applied to secondary aerosol. The multivariate method needs only the chemical composition of particle at the receptor to estimate both the source profile and the source contribution (Hueglin et al, 2000). This method needs to identify the contribution of a source on the basis of the variability in the chemical components (QUARG, 1996). It is assumed that if two or more chemical components are emitted from the same source, their variability observed at a receptor point will be similar. The method detects the common variability and infers source identity by comparing the element with common variability to the element with a specific source. Chemical components from emission sources are not required, but a large number of observations are needed and statistical independent source tracers are required for each major source type.

Apart from the techniques as mentioned above, the source apportionment of particulate matter has been conducted by using linear regression analysis of the PM_{10} with other pollutants, such as CO, NO_x, O_3 and benzene, to estimate the road contribution to PM_{10} within UK urban areas as performed by the Quality of Urban Air Group (QUARG, 1996). Later, this technique has been extended and refined by the Airborne Particles Expert Group (APEG) and new methods developed which have confirmed the basic conclusions of the third report of the Quality of Urban Air Group (APEG, 1999). A review of the UK NAQS on future PM_{10} levels was also derived from the receptor model method developed within the Airborne Particles Expert Group (APEG) framework (Stedman, Linehan and Conlan, 2001). The Airborne

Particles Expert Group (APEG) used CO or NO_x as a tracer of the traffic related emissions, and the linear regression obtained from the relationships between daily or hourly mean PM_{10} and CO or NO_x was employed to estimate the level of PM_{10} generated from road traffic and the PM_{10}, which does not arise from the road traffic (background + resuspended dust) (APEG, 1999). When the urban background concentration of a species was subtracted from its roadside level, it gives the concentration of the 'roadside enhancement' of each species. The roadside enhancement is the difference between roadside and background observations (APEG, 1999). The Airborne Particles Expert Group (APEG) used this concept to study the relationship between PM_{10} and NO_x induced by traffic. Using this concept, the resuspended dust near the roadside could also be obtained. When the relationship between the roadside enhancement of PM_{10} and CO or NO_x reaches the intercept where there is zero influence from vehicle emissions, the PM_{10} level corresponds to the PM_{10}, which does not arise from road traffic and urban background pollution. This PM_{10} is assumed to equal the resuspended dust at the roadside.

The technique using linear regression of the roadside enhancement was applied in this research, because a comprehensive study of chemical components in particulate matter in Thailand has not been conducted. So far, only some common heavy metals in aerosol particle have been investigated e.g. Pb, Zn, Cu (Kaew-Ngarm, 2000). At the start of the analysis the correlations of PM_{10} - CO, and PM_{10} - NO_x at three roadside sites: Dindaeng, Ladphrao, and Thonburi Electricity during 1997 to 1999 were studied. The PM_{10} observed by the Beta-ray method was employed for this purpose as more data are available than those from the gravimetric high volume method. CO was observed by the Non-dispersive Infrared (NDIR) method. The study results at this step (Table 5.17) indicated that PM_{10} and CO showed stronger correlations than PM_{10} and NO_x. PM_{10} and CO were chosen for further study, in which the observed PM_{10} by the high volume gravimetric method was used instead of the Beta ray method, so as to be consistent with the standard method regulated in the Thai Ambient Air Quality Standard. The gravimetric instrument is also the reference monitoring method for the limit values defined in the EU 'Daughter Directive' on Ambient Air Quality Assessment and Management (Stedman, Linehan, and Conlan, 2001), which is the regulation in the UK.

The PM_{10} was collected by the gravimetric high volume sampler for a period of 24 hours every sixth day. The observed hourly CO was averaged to daily CO. The paired roadside-urban background air quality monitoring sites were the Dindaeng-Ramkhumhaeng, and Ladphrao-Klong Jun sets. The pairing for Thonburi Electricity site was changed from the Singharach station to the Nonsi station, as mentioned in the previous chapter. Because of the influence of the PM_{10} emissions from industries locating near to this site, higher PM_{10} than that of Thonburi Electricity site was always found at Singharach site. So, this site did not fit the purpose of the analysis in this chapter. The Nonsi urban background station was used instead. The daily means of PM_{10} and CO of urban background sites were subtracted from their pairs of roadside sites to give the daily roadside enhancements of each species. The paired daily mean enhancements of PM_{10} and CO for a given site between 2001 and 2003 were plotted and the PM_{10} at the intercept point of the linear regression was taken as equal to the resuspended dust. The percentage of resuspended dust in Bangkok was estimated.

The correlations between PM_{10} and CO or NO_x are depicted in Table 5.17. The strongest correlations are shown at Dindaeng and the weakest at Ladphrao. The relatively weak correlations at Ladphrao during 1997 - 1999, and Thonburi Electricity in 1998 and 1999 suggest that non-vehicle sources made a large contribution to PM_{10} level at these sites during those years. The stronger correlations with CO and NO_x indicate the importance of vehicle emissions at the Dindaeng station. When data availability is more than 80%, the correlations between PM_{10} and CO are apparently greater than that the correlations between PM_{10} and NO_x. Hence, the former was chosen for further study of the resuspended dust in Bangkok.

Table 5.17 Correlations (r) between daily average of PM_{10} and other pollutants

Station	Year	CO	NO_x
Dindaeng	1997	0.8661 (95%)	0.8589 (95%)
	1998	0.6964 (88%)	0.6747 (58%)
	1999	0.7164 (72%)	0.6779 (17%)
Ladphrao	1997	0.4253 (84%)	0.2163 (86%)
	1998	0.1019 (75%)	0.3270 (55%)
	1999	0.1147 (45%)	0.3297 (49%)
Thonburi Electricity	1997	0.7364 (94%)	0.6951 (92%)
	1998	0.4730 (89%)	0.4040 (88%)
	1999	0.5162 (47%)	0.3194 (49%)

(x%) = % data available

The relationships of roadside enhancement between PM_{10} and CO at Dindaeng, Ladphrao, and Thonburi Electricity stations are illustrated in Figures 5.6 to 5.8, respectively. Due to the sampling by the gravimetric high volume method, the pooling of PM_{10} or CO between two sites, following the pooling between PM_{10} and CO simultaneously, a smaller number of data points and a weaker correlation than those shown in Table 5.17 can be expected. The resuspended dust taken from the intercept of the relationships is summarized in Table 5.18. It is found that the fractions of resuspended dust at three roadside sites were very similar. Hence, it can be concluded that around 20-25% of PM_{10} observed near roadside sites in Bangkok was attributed to the resuspended dust. It should be noted that the prediction of particulate matter near roadsides in a Gaussian-based model, such as the GRAM model, accounts only the emission from vehicle emissions and does not include secondary particulate matter, and resuspended dust.

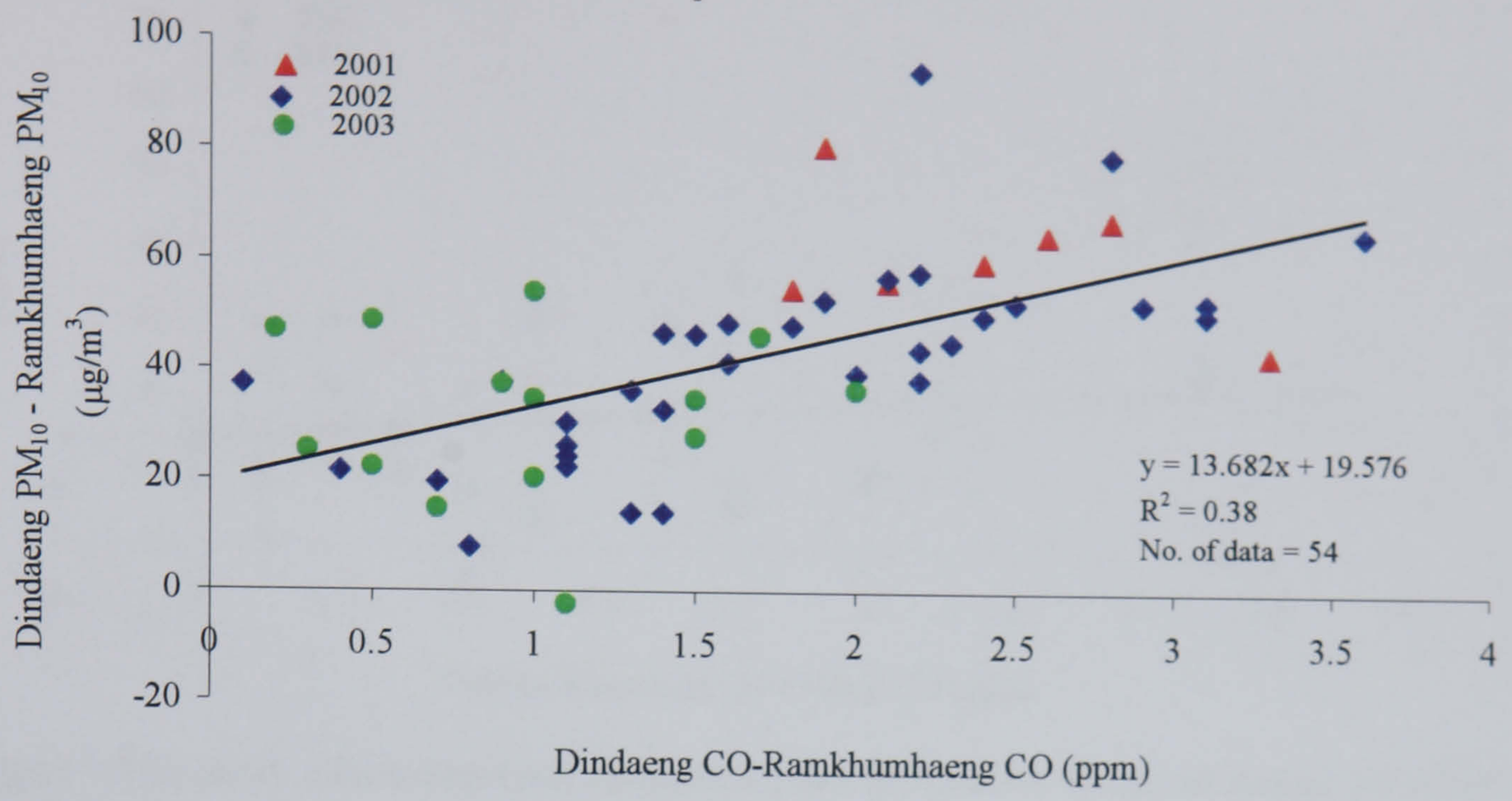


Figure 5.6 Roadside enhancement and resuspended dust at Dindaeng during 2001-2003

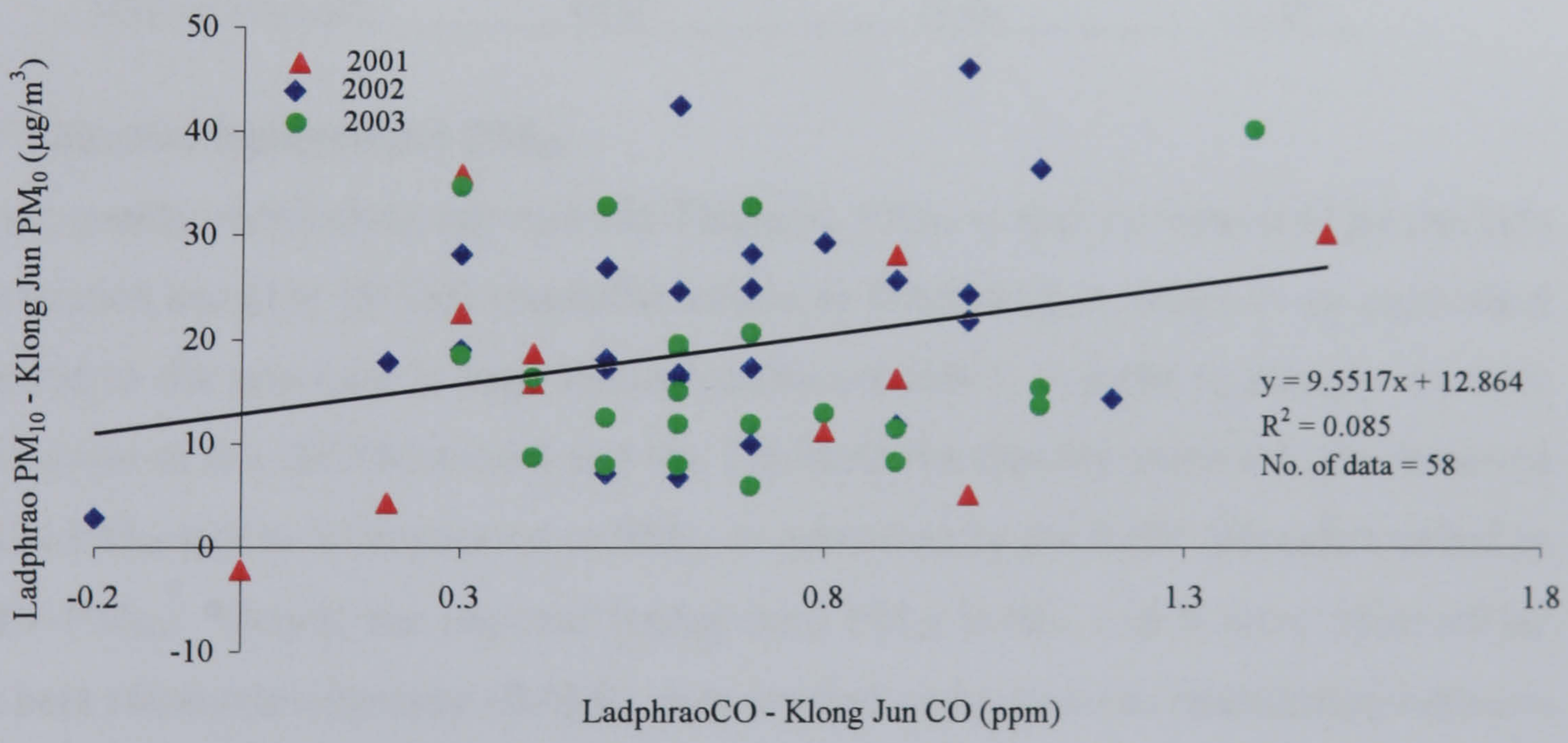


Figure 5.7 Roadside enhancement and resuspended dust at Ladphrao during 2001-2003

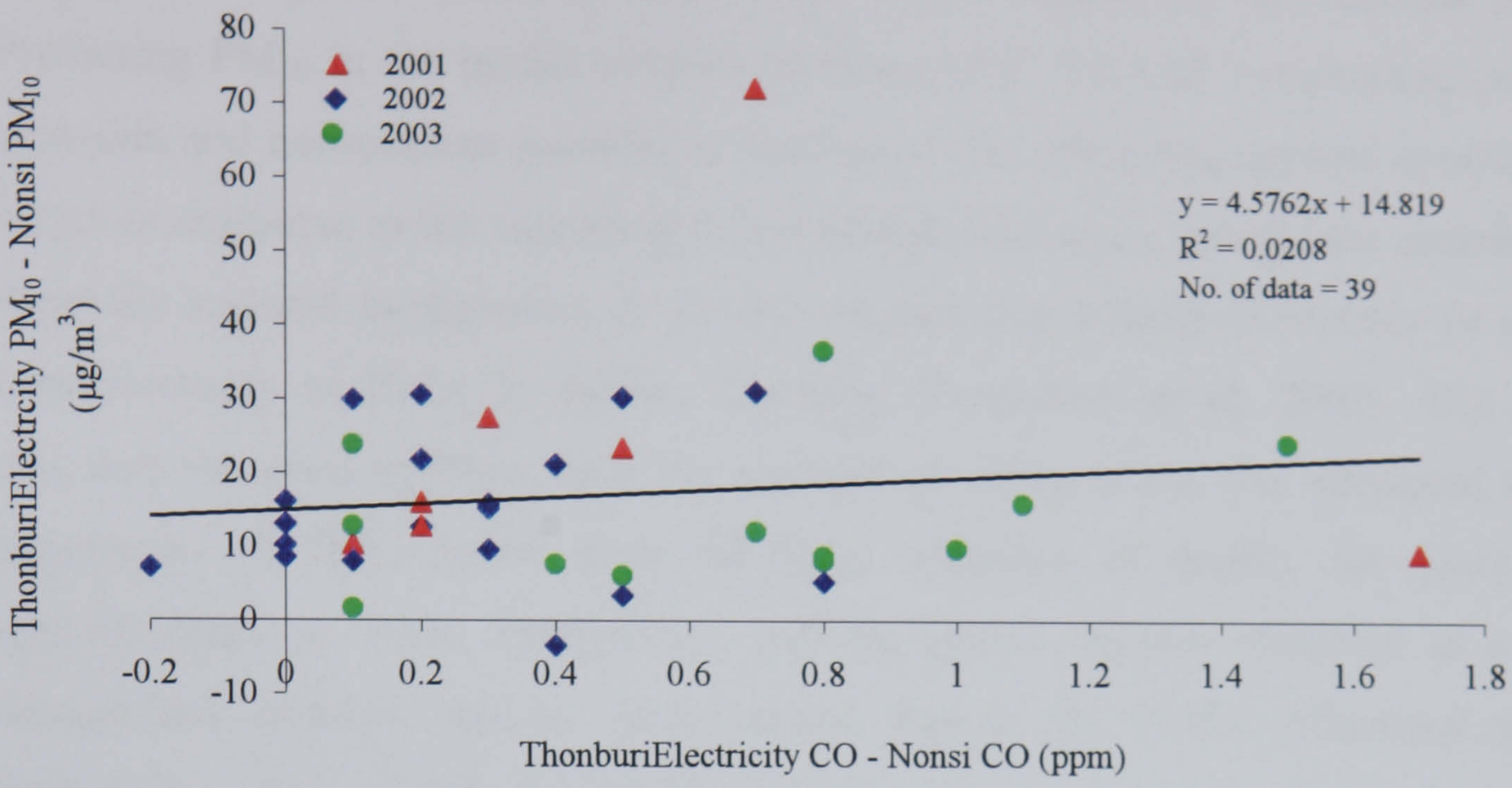


Figure 5.8 Roadside enhancement and resuspended dust at Thonburi Electricity during 2001-2003

Table 5.18 Resuspended dust and its fraction at roadside sites in Bangkok between 2001 and 2003

Station	Annual average PM_{10} ($\mu g/m^3$)	Resuspended dust ($\mu g/m^3$)	Fraction
Dindaeng	93.17	19.58	0.2101
Ladphrao	61.13	12.86	0.2104
Thonburi Electricity	64.80	14.82	0.2287

5.7 Regional background PM_{10}

In air quality monitoring networks in Thailand, PM_{10} is mainly measured by the beta attenuation monitor (BAM) (hereafter called as BAM-PM_{10}), which is an equivalent method to the gravimetric high volume method (GHV). In order to comply with the prediction of the GRAM model and the Thailand Air Quality Standard, the observed BAM-PM_{10} had to be converted to PM_{10} as measured by the GHV (hereafter called as GHV-PM_{10}). Hence, the regional background PM_{10} levels, which were observed by the beta attenuation monitor (BAM), were studied along with the relationship between the beta attenuation monitor and the gravimetric high volume method so as to get a correction factor for converting the regional background BAM-PM_{10} to GHV-PM_{10}. In the process of data analysis, an exceptional BAM-PM_{10} level was found at Thonburi Electricity station. The details are discussed in Appendix 1. Due to the major forest fires which occurred in Indonesia, the impact of these events on the regional background PM_{10} in Thailand is also discussed and detailed in Appendix 1.

5.7.1 Regional background BAM-PM_{10}

Regional background PM_{10} is one of the inputs needed by the GRAM model. Predicting PM_{10} in the model consists of three parts: (1) road contribution (vehicle emission and non-exhaust particle, or road dust), (2) urban background contribution which is attributed to the sources in urban background areas, and (3) the contribution from the regional background. A similar concept was employed recently in source apportionment of PM_{10} in Berlin, Germany (Lenschow et al, 2001). The study assumed the level of PM_{10} near the roadside in urban areas was attributed to the summation of PM_{10} levels from the local influence of traffic, the sources of agglomeration in urban background, and the global sources observed at a rural background location. Results demonstrated that at the traffic influenced station Frankfurter Allee in 1998, around 36% of PM_{10} was accounted by sources outside the agglomeration or the regional background. In Spain, the regional background PM_{10} consisted of around 40% of the PM_{10} levels at a kerbside site (Alastuey et al, 2003). Dingenen et al (2004) found that the PM level at urban background sites in some areas in Europe could be as high as PM levels at kerbside sites in other parts of Europe. They stated that it showed the importance of regional PM background. It was clearly seen that the contribution of the regional background PM_{10} at roadside sites should not be neglected.

The rural sites and/or sites near small settlements are usually used as measurements of clean background air suitable for comparison with urban or industrial areas (Branis and Domasova, 2003). Regarding the criteria proposed by the European Environment Agency, the monitoring at rural stations was categorised into (Larssen et al, 1999)

(1) Near-city background stations: located in rural/agricultural areas, with a distance of 3-10 km from built-up areas and other major sources.

(2) Regional stations: located in rural/agricultural areas, with a distance of 10-50 km from built-up areas and other major sources.

(3) Remote stations: located in rural/natural areas, with a minimum distance of 50 km to built-up areas and other major sources.

Studies describing in detail particulate pollution in rural areas are scarce and most of them had been undertaken in Europe. In Switzerland, Monn et al. (1995) observed the annual mean PM_{10} by using cascade impactors. They found levels of between 16 and

18 $\mu g/m^3$ at rural sites on the Swiss Plateau, and 40% lower than the rural sites at the alpine sites of Davos at 1600 m above sea level (a.s.l) and Montana (1300 m a.s.l). The annual mean gravimetric high volume PM_{10} (GHV-PM_{10}) measurements of 10.8 and 14.4 $\mu g/m^3$ were observed at rural sites in the Basel area during April 1998 - March 1999 (Roosli et al, 2001). During four-year monitoring of PM_{10} with GHV at the rural sites of Chaumont (1140 m a.s.l.) and Payerne (490 m a.s.l., typical altitude of the Swiss basin), Gehrig and Buchmann (2003) found that the annual mean PM_{10} was 10.2 - 12.1 $\mu g/m^3$ at Chaumont, 19.3 - 23.2 $\mu g/m^3$ at Payerne. The regional background levels of PM_{10} found in Spain during 1999 – 2001, which was observed by the GHV sampler, were 15 $\mu g/m^3$ in the Atlantic regions and 20 $\mu g/m^3$ in the other Spanish regions (Alastuey et al, 2003). The 1998 annual mean PM_{10} observed by using a Tapered Element Oscillating Microbalance (TEOM) was 14, and 17 $\mu g/m^3$ at rural sites in Rochester and Narberth respectively, and 10 $\mu g/m^3$ at a remote site in Lough Navar in the UK (AEAT, 2004). A concentration slightly higher at 18-19 $\mu g/m^3$ was observed at a rural site in South Somerset District during 1998-2000 (Holmes, 2004). The average PM_{10} level of 24 $\mu g/m^3$ was observed in an air monitoring campaign carried in Illmitz, a rural background site in eastern Austria from October 1999 - 2000 (Schneider et al, 2004).

Short term mean PM_{10} at rural sites have also been observed. The abundance and origin of atmospheric organic PM_{10} at two rural sites in Portugal where eucalyptus forests covered the region were observed during the summer period of August 1996 (Alves, Casimiro, and Duarte, 2001). The means of GHV-PM_{10} measurements were 44.1 and 30.4 $\mu g/m^3$. A much lower PM_{10} level of 15 $\mu g/m^3$ was observed at Peer, a small, rural village in the Province of Limburg, Belgium in September 2000.

The very recent comprehensive work undertaken by Dingenen et al (2004) proposed a background annual average PM_{10} of 7.0±4.1 $\mu g/m^3$ for continental Europe. Based on the data obtained from 31 sites in Europe, the authors observed that the 5 percentile values at rural and near city background sites were similar to the annual average concentrations observed at natural background sites. Then, they derived a European continental background level by taking the average of the natural background annual mean concentrations and the rural and near city background 5 percentile values. In

USA, non-urban aerosol concentrations were measured at remote sites from 1988 through to 1993. The eastern US PM_{10} concentrations were in a range of 12-25 $\mu g/m^3$ (CAPITA, 1996). The lowest non-urban PM_{10} concentrations of 5-10 μg/m3 were measured over the central mountainous states. Higher levels of 10-20 $\mu g/m^3$ were recorded over the southwestern USA, as well as over the Pacific states from California to Washington. More recent observations at three sites in Maine, USA, during 1998-1999 showed the annual mean PM_{10} in a range of 10-14 $\mu g/m^3$ (Department of Environmental Protection, 2002).

It can be seen that observations of the mean PM_{10} in clean rural areas were conducted at different areas in Europe and America and the findings showed a geographical variation even in the same country. This is due to a mixture of factors including local sources, long-range transport, specific climatic situations (Branis and Domasova, 2003), and a distance from built-up areas and other major sources. These factors influence ambient concentrations of particulate matter.

In Asia, air quality monitoring or research campaigns on PM have been focused on the impact on human health and welfare. Hence, most of measurements were conducted in urban or suburban areas, for example, Brunei, Darussalam (Radojevic and Hassan, 1999), Lebanese urban areas (El-Fadel and Massoud, 2000), Kwangju, Korea (Kim, Kim and Oh, 2001), XiAn, China (Zhang, 2002), Dhaka, Bangladesh (Salam et al, 2003), Hanoi, Vietnam (Hien, Bac and Thinh, 2004), the urban area of Kansai, Japan (Ma et al, 2004). Very little continuous monitoring found in literature reviews has been conducted in clean rural or remote sites in Asia. A study was undertaken in Taiwan at national parks between 1994 and 1997. The annual mean PM_{10} (using the beta-gauge monitors) of 18.7±5.6 and 21.4±4.8 $\mu g/m^3$ were observed at national parks in Yangming (north of Taiwan) and in Hengchuen (south of Taiwan) respectively (Yang, 2002). The mean concentration with seasonal variation of PM_{10} in rural areas in Bangladesh was observed at 56.1±34.6 $\mu g/m^3$ (Rib, 2001). A study conducted by the low flow gravimetric method at Nagarkot, a hilltop site on the eastern edge of the Kathmandu Valley, approximately 800 m above and 32 km east of Kathmandu, Nepal during 1999–2000 (Carrico et al, 2003) demonstrated that the average PM_{10} levels were 29±15, 81±76, and 11±15 $\mu g/m^3$ during the winter period

(October–January), peak season (February–May), and summer monsoon season (June–September) respectively. Rami (2004) studied PM in small towns in Malaysia in 1997, the year of severe haze events, 1998 when no major haze incident, and 2002, the most recent year of haze event. The annual mean PM_{10} observed in 1998 at the Indera Mahkota Municipality and the Jerantut District in East Malaysia were 25.8, and 32.3 $\mu g/m^3$ respectively. The average PM_{10} in Asia also show a geographical variation and seems to demonstrate a higher level than that of Europe and USA.

In Thailand, the monitoring at rural or natural sites has not been included in the nationwide air quality network. The network comprises two monitoring types: the roadside station and the general station (located at the urban background or the urban centre, away from roadside by between 50-100 m). According to the observations of Dingenen et al (2004), the 5 percentile values of PM_{10} at rural and near city background sites is similar to the annual average concentrations observed at natural background sites. This finding was applied in this research to obtain the regional background PM_{10}. The daily PM_{10} observed by the beta attenuation monitor (BAM) at stations located outside of the Bangkok Metropolitan Region (BMR) between 1997 and 2003 was analyzed for 5 percentiles in each year. The average and standard deviation of 5 percentiles in a year in question from all stations and the total data were calculated. Due to limited data available from general (urban background) stations in some provinces, the data then had to be taken from roadside sites. However, the traffic in regional provinces is not as dense as in Bangkok. The description of all monitoring sites is shown in Table 5.19. The 5 percentile PM_{10} obtained after this step was compared to the 5 percentile of PM_{10} values observed at two urban background stations sited in the outer zone of Bangkok over the same period. The regional background BAM-PM_{10} for area of Bangkok was considered from the agreement of the 5 percentile obtained from the station outside BMR and the stations sited in the outer zone of Bangkok.

Table 5.19 Air quality monitoing stations located in regions of Thailand

Station	Type	Region	Location
Ayuttaya	General	Central	The Phra Nakhon Si Ayuttaya College
Chiang Mai	General	North	Chiang Mai Government Service Center
Lumpang	General	North	Lampang Provincial Administration Office
Suratani	Roadside	South	Suratthani Distric Administration Office
Hatyai	Roadside	South	Hatyai Meang
Chonburi	General	East	Chonburi General Education Office
Rayong	General	East	Rayong Telephone Services Center
Khonkaen	Roadside	Northeast	Khon Kaen Permanent Secretary House
NakornRatchasima	Roadside	Northeast	The Resident of Commanding General 21th
Ramkhumhaeng	General	Outer zone of Bangkok	Playground, Ramkhumhaeng University
Klong Jun	General	Outer zone of Bangkok	Residential area, National Housing Authority

Source: PCD, 2004

The 5 percentile PM_{10} concentrations observed in regional areas outside of the Bangkok Metropolitan Region (BMR) are shown in Table 5.20. The table demonstrates that the percentage of sites, with daily PM_{10} capture over 80%, was just 35%. However much of the remaining data reveals the baseline PM_{10} level in regional areas outside the Bangkok Metropolitan Region (BMR). For example, at Rayong station (East), the 5 percentile PM_{10} at this station were obtained from the data, even though data capture was <50% of daily values. The table shows that the regional background PM_{10} could be as low as 15 $\mu g/m^3$ in some areas. A plot of the average and standard deviation (S.D.) is illustrated in Figure 5.9. The figure shows that all of the average values between 1997 and 2003 are in the range of 20-30 $\mu g/m^3$ and the grand average is 23.3±7.3 $\mu g/m^3$. When the 5 percentile PM_{10} observed at the urban background sites located in the outer zone of Bangkok (Table 5.21) were added to the plot (Figures 5.10 and 5.11), it was found that the Bangkok PM_{10} values fell into the range of the average + S.D., except the PM_{10} value at Klong Jun in 2003 which was about 3 $\mu g/m^3$ less than the average value observed outside the BMR. This might due to just three data sets being available outside the BMR in 2003. Finally, the regional background PM_{10} concentration for Bangkok was taken from the range of the average + S.D., which was roughly around 30 $\mu g/m^3$. During the Indonesian haze event in 1997, the annual mean PM_{10} and five percentile PM_{10} in southern areas of Thailand was increased, but this was a temporary influence. This event is discussed in Appendix 1.

Table 5.20 Five percentile daily PM_{10} observed at stations outside BMR unit: $\mu g/m^3$

Station	1997	1998	1999	2000	2001	2002	2003
Ayuttaya	N/A	21.4*****	23.9*****	N/A	N/A	N/A	N/A
Chiang Mai	N/A	13.0****	26.0***	16.0**	19.0***	16.0*	21.8****
Lumpang	N/A	23.1***	22.3*	28.1*	17.0**	22.7***	N/A
Suratani	29.6*****	13.8**	15.0***	16.0*	18.0*	38.0*****	N/A
Hatyai	23.0*****	18.0*****	N/A	24.1*****	22.0*****	21.0***	N/A
Chonburi	N/A	22.9*****	20.4**	24.0*	29.0*	37.0*	33.9*****
Rayong	N/A	15.1*****	14.5*****	15.6*****	16.0*****	30.2*****	N/A
Khonkaen	N/A	33.5****	32.2*	27.0*	21.0*	22.0*	N/A
NakornRatchasima	N/A	24.3*****	47.0*****	31.5*****	19.9**	22.9*	N/A
Average	26.3	20.6	25.1	22.8	20.2	26.2	27.8
S.D.	4.7	6.5	10.5	6.2	4.1	8.0	8.6
Average (all data)	23.3						
S.D. (all data)	7.3						

Note:
N/A = data not available
* = data >80%
** = data >70%
*** = data >60%
**** = data >50%
***** = data <50%

Table 5.21 Five percentile daily PM_{10} at urban background stations in Bangkok unit: $\mu g/m^3$

Station	1997	1998	1999	2000	2001	2002	2003	Average
Ramkhumhaeng	29.7	31.7	28.9	29.7	21.0	30.9	39.2	30.2
Klong Jun	34.8	30.0	25.7	25.9	20.2	25.8	24.6	26.7

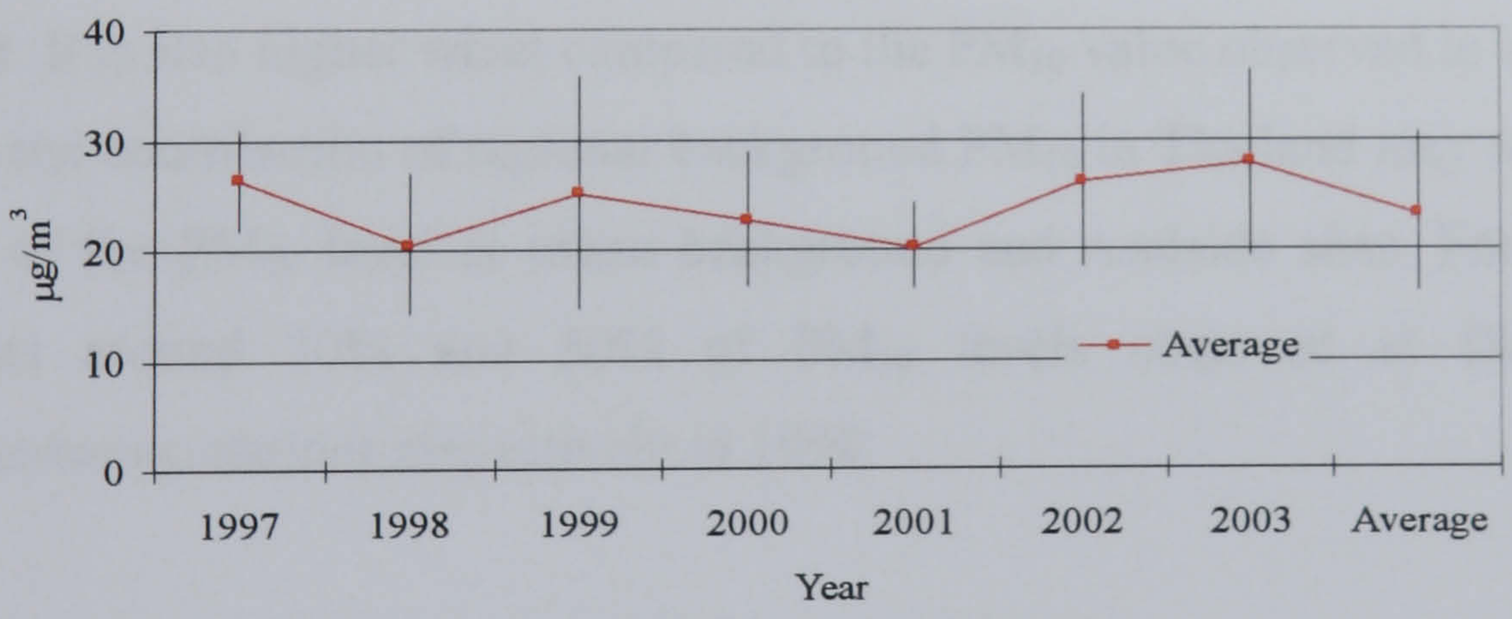


Figure 5.9 Five percentile PM_{10} outside BMR

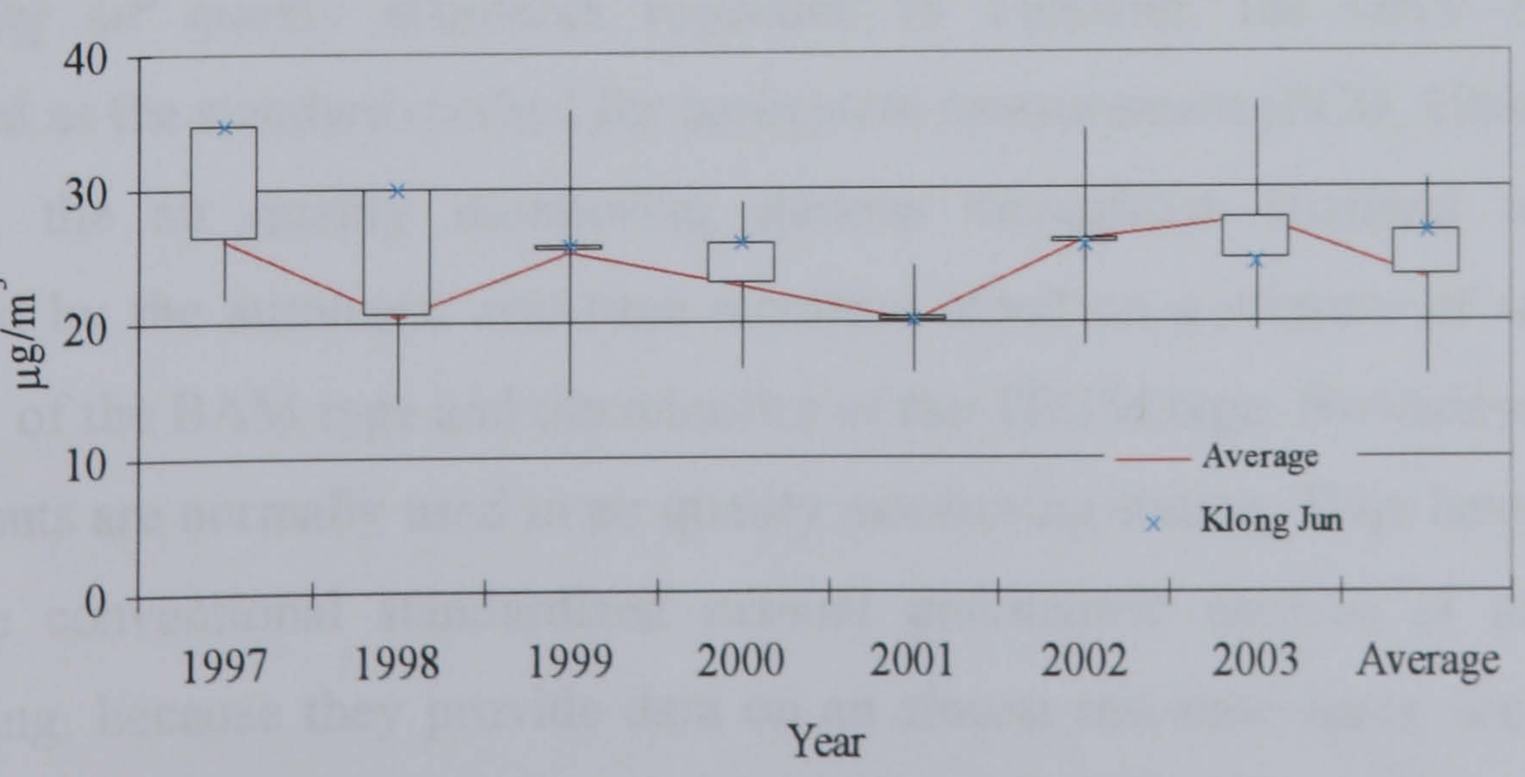


Figure 5.10 Five percentile PM_{10} at stations outside BMR and Klong Jun

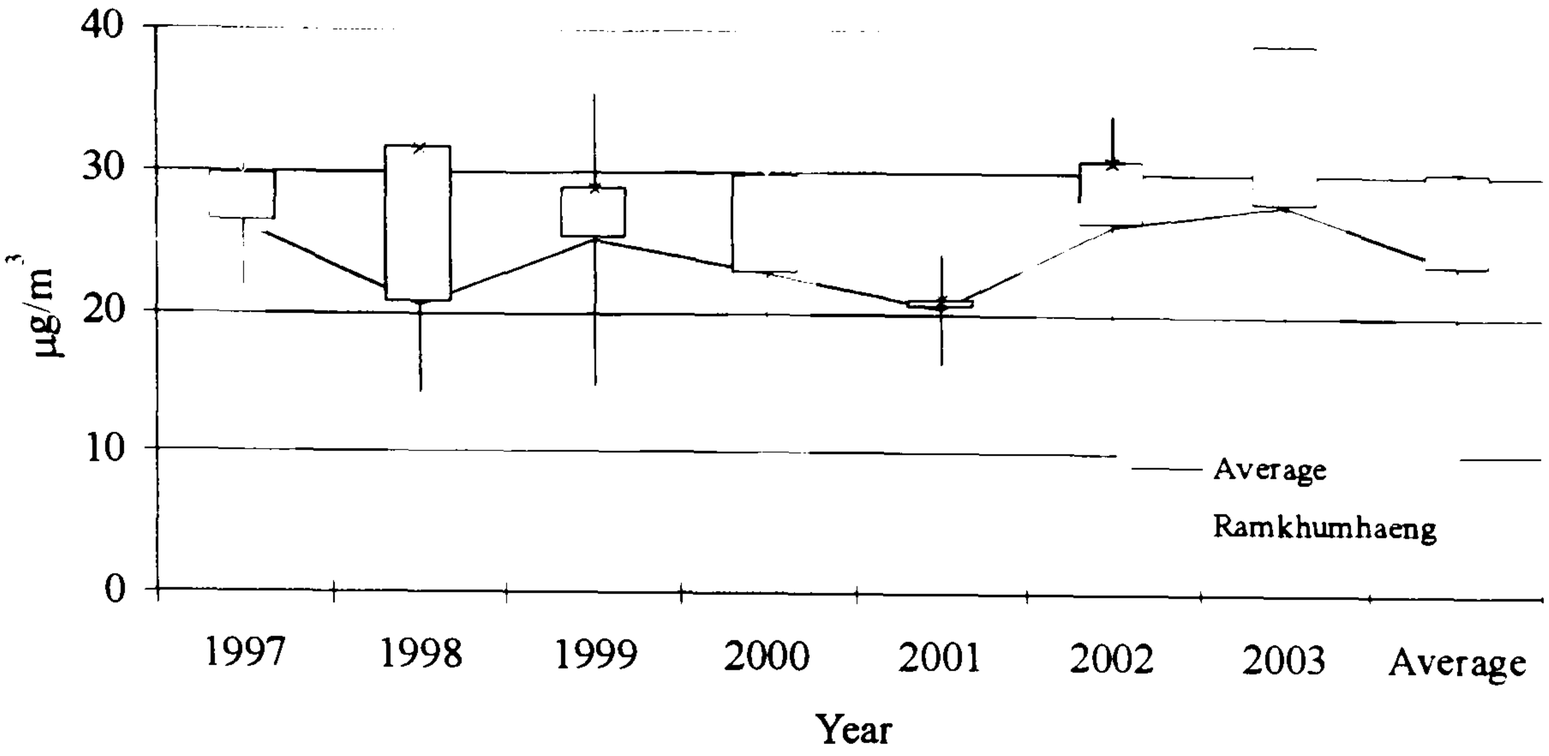


Figure 5.11 Five percentile PM_{10} at stations outside BMR and Ramkhumhaeng

As the results indicated, the regional PM_{10} in Thailand appears to lie in a range of 23.3±7.3 µg/m^3. This is a bit higher than those observed at national parks in Taiwan, which were 18.73±5.6 and 21.4±4.8 µg/m^3 under the same method (BAM). However it seems close to the annual mean PM_{10} of 25.8 and 32.3 µg/m^3 measured in two small towns in Malaysia in 1998. It is also higher than the range of around 10-25 µg/m^3 found in Switzerland, Spain, and Austria. In UK, when the factor of 1.3 (DETR, 1999) has been applied to TEOM-PM_{10}, the results fall into the same range as those cities in Europe, which means the regional PM_{10} in the UK is lower than that in Thailand. It is also higher when compared to the PM_{10} value observed in USA. Hence, it seems the contribution of regional background PM_{10} in Thailand may make a larger fraction of the PM_{10} level at urban background and roadside sites. For example, it represents around 30% and 50% of PM_{10} levels observed at Dindaeng and Ramkhumhaeng stations respectively in 1998.

5.7.2 Relationship between BAM-PM_{10} and GHV-PM_{10}

Regarding air quality standards regulated in Thailand, the GHV method was stipulated as the standard method for particulate measurement (PCD, 2004). Whilst, in practice, the air quality monitoring stations throughout Thailand were mainly measured by the automatic real-time monitors based on a mixture of samplers: the majority of the BAM type and the minority of the TEOM type. Nowadays, automated instruments are normally used in air quality monitoring station. They have advantages over the conventional standardized manual gravimetric method of particle mass monitoring, because they provide data on an almost real-time basis, are a cost- and

labour-effective method (Charron et al, 2004). allowing analysis of diurnal trends and have the ability to track the passage of pollution episodes (Green, Fuller and Barratt. 2001). However, several previous investigations (for instance. Ayer. Keywood and Gras, 1999; Chung et al, 2001; Green, Fuller, and Barratt, 2001; Vega et al 2003: Charron et al., 2004) have indicated that the reference gravimetric method and the automated instruments, such as TEOM, gave different results. Charron et al (2004) pointed that the extent of differences between the TEOM and gravimetric methods was not universal and the relationship between them should be examined for each site.

Previous work also indicated that the observed data between the GHV and the BAM were different. Mass determination in BAM is based on the attenuation that beta-radiation undergoes as it passes through an exposed filter. Similar to TEOM. the sampling system of BAM is also heated to prevent the condensation of water in the sampling line (Salminen and Karlsson, 2003; Hauck et al, 2004). The inlet of the TEOM system is usually heated to 50°C (APEG, 1999), whilst mild heating is used in the BAM sampling system (Wilson et al, 2002). Dalager (1975) conducted a comparative study of four PM measuring methods, viz. the OECD (smokeshade). the AISI tape sampler, the beta attenuation monitor, and the high volume method, in two Danish cities. The results indicated that only the high volume sampler could give a reasonably correct measurements of PM. However, a comparative measurement on $PM_{2.5}$ at Bakersfield, California, in 1998/99 (Chung et al, 2001) found that the BAM correlated well with filter-based samplers. A good correlation of R^2= 0.98 between the two methods was also found in Christchurch, New Zealand (Ministry for the Environment, 2003). Very recently, the GHV, BAM, and TEOM were used to observe the PM levels (PM_{10} and $PM_{2.5}$) at three urban sites and one rural site in Austria over 1-year time (Hauck et al., 2004). The devices were placed in an air-conditioned container. The sampling lines of both TEOM and BAM were heated to avoid water condensation. The results show that the GHV always yielded the highest mean PM levels and the BAM the lowest. During the winter when the average temperature was very low (below 15°C), the GHV showed higher levels than the TEOM and the BAM, most of the time. The results showed a good agreement amongst the various methods for summer and when the nitrate content in particles was low. The correction for the nitrate content observed in GHV-PM_{10} to TEOM-

PM_{10} measurements improved the agreement between the GHV and TEOM for winter data when nitrate content in GHV-PM_{10} samples was high.

A field study carried out at a clean background air in Finland during autumn and early winter conditions with some precipitation (Salminen and Karlsson, 2003) found that PM_{10} levels observed by the BAM sampler gave slightly higher concentrations than the gravimetric low volume sampler (GLV) and the mean ratio (monitor/reference sampler) of all results was 1.06 ± 0.12, when the relative humidity was over 85% and the daily temperature was below 0°C. The reason for the difference was referred to in Chang et al's work (2001), who conducted a study in Taiwan. It should be noted that the BAM sampler used in these two studies was not housed in an air-conditioned shelter. They were sampled at ambient temperatures and relative humidity, but the sampling system was heated a few degrees above ambient temperature to prevent water condensation (Salminen and Karlsson, 2003). Chang and his team compared the BAM with the GHV, and they found that when the deliquescence point was exceeded, the BAM gave a higher PM_{10} level and they found that the increasing ambient relative humidity increases the difference between BAM-PM_{10} and GHV-PM_{10} (Chang et al, 2001). They pointed that the overestimatation of PM_{10} levels in BAM was attributed to BAM's filters, which were not conditioned before detection and aerosol particles collected on the filter may absorb water when the deliquescence point was exceeded. Nevertheless BAM was used in the Taiwan Air Monitoring Network (Chang et al, 2001). From literature reviews, it can be seen that the relationship between the BAM and GHV differs from place to place. Green, Fuller, and Barratt (2001) recommended that the correction factors applied to TEOM data should incorporate the local geographical and temporal variability. However, in current practice, a single correction factor has been used for the relationship between the gravimetric method and automated monitor, for example the factor of 1.3 was used in the UK for TEOM-gravimetric conversion (DETR, 1999), and 1.34 for the radiometric monitor-gravimetric method in Berlin, Germany (Lenschow et al, 2001).

In Thailand, the Pollution Control Department (PCD) has used the BAM for many years in the national air quality monitoring network. Due to the variability between the gravimetric method and BAM found in previous work and the recommendation

that any correction factor applied to an automated instrument data should incorporate the local geographical and temporal variability (Green, Fuller, and Barratt, 2001), the relationship between the BAM-PM_{10} and the GHV-PM_{10} was investigated for an area of Bangkok so as to obtain the correction factor. The correction factor was then applied, for the purpose of this research, to convert the regional background PM_{10} observed by BAM to the PM_{10} in the standard method or GHV-PM_{10}. The regional background GHV-PM_{10} obtained at this step will be used for estimating the PM_{10} in the Bangkok GRAM model.

The simultaneous measurement of PM_{10} by the BAM and GHV started in 2001 and the relationship between the two methods has not been completed for Bangkok. Thus, the relationship for the three-year data set during 2001-2003 is under investigation. At every monitoring site, the BAM is housed in an air-conditioned container. The inlet is on the top of the container and its tube is heated to prevent water condensation. The PM_{10} high volume sampler was collocated on the top of the container. All monitoring sites are at the ground level. The parallel 24-h measurements at three roadside and four urban background stations, are shown in Table 5.22.

Table 5.22 Air quality monitoring stations and the description of their locations

Station	Type	No. of paired data	Location
Dindaeng	Roadside	107	in front of resident flats, traffic flow ~ 120000 veh/day
Ladphrao	Roadside	111	beside a Police station, traffic flow ~ 85000 veh/day
Thonburi Electricity	Roadside	105	in front of an electricity-distribution station, traffic flow ~ 65000 veh/day
Ramkhumhaeng	Urban background	90	in a university playground, ~ 100 m away from a busy street
KlongJun	Urban background	125	residential area
Singharach	Urban background	110	next to a local road and near to a school entrance
Nonsi	Urban background	137	located behind a building in a school precint, ~100 m from a main road

At each station, the levels of the BAM-PM_{10} and GHV-PM_{10} during 2001-2003 were plotted in order to see the trend in observations. The average PM_{10} and standard deviation (S.D.) of the annual, and seasonal, together with the ratio of GHV/BAM were calculated. The seasonal ratios of GHV/BAM at all stations were plotted to reveal the seasonal variation within the station and amongst the stations during 2001-2003. As discussed earlier there are three seasons in Thailand: the rainy (16 May-15 October), the winter (16 October-14 February), and the summer (15 February-15

May) (Meteorology Department, 2003). The correlation between the BAM-PM_{10} and GHV-PM_{10} over the study period was calculated using linear regression and R^2, with and without an intercept. The correction factor for assessing the GHV-PM_{10} from the observed BAM-PM_{10} in Bangkok was determined based on the geographical location at both roadside and urban background sites.

Figure 5.12 shows the obvious trend of higher GHV-PM_{10} concentrations than BAM-PM_{10} concentrations at all stations, except at the Thonburi Electricity roadside station. The PM_{10} observed by the BAM and GHV at the Thonburi Electricity station was very close, but a slightly higher concentration by mass was found in the GHV as seen in Table 5.23. The reason is discussed in Appendix 1. However it can be concluded that, in Bangkok during 2001-2003, the observed PM_{10} from the GHV were greater than the BAM. This finding is in contrast to the studies undertaken by Chang et al (2001) and Salminen and Karlsson (2003) because the measurements in their studies were set up at ambient conditions, whilst the BAM in this research was housed under controlled conditions in air-conditioned containers, which can prevent water collecting on the filter tape in high humidity or rainy climates. The higher BAM-PM_{10} found in their studies seems to arise from the absorption by the inorganic mass of aerosol on the filter tape, giving a greater effect to the total PM_{10} mass than the error arising from the loss of volatile organic aerosol due to the heated inlet tube. Hence, in order to avoid an error due to the water collected on the filter tape, especially in a national monitoring network, the device should be kept at a controlled temperature and relative humidity or in an air-conditioned container.

Table 5.23 shows that almost all GHV-PM_{10} measurements were greater than BAM-PM_{10}, except the observations at the Ramkhumhaeng and Sigharach sites in rainy and summer seasons in 2003 which showed lower PM_{10} concentrations. This is because the filter-based methods were also not free from errors, which may occur during and after the collection. For example, the volatilisation of semi-volatile components during collection, the adsorption of semi-volatile organic gases onto or from the collected PM and filter media, the content of particle-bond water, and the retention of water by the filter (Charron et al, 2004). The higher GHV-PM_{10} found in this research is consistent with a study conducted by Hauck et al (2004). Their results showed that the GHV gave higher PM mass than the BAM. Both studies were similar in the way

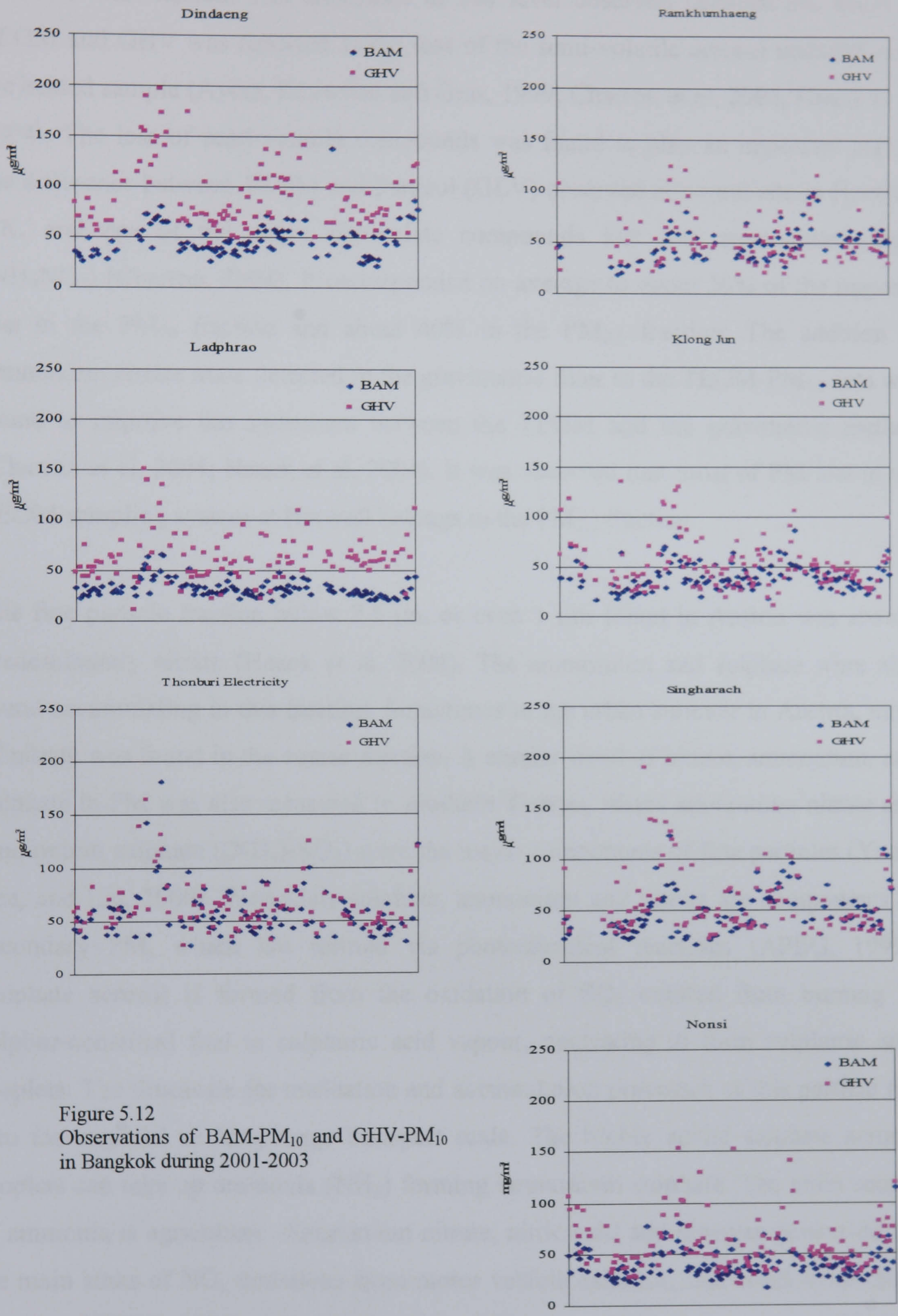


Figure 5.12
Observations of BAM-PM_{10} and GHV-PM_{10} in Bangkok during 2001-2003

in which their devices were kept in an air-conditioned container and the inlets of the monitors were heated. The difference of PM level observed between the BAM or TEOM and GHV was reported as the loss of the semi-volatile aerosol material from the heated sample (Ayers, Keywood and Gras, 1999; Charron et al, 2004; Hauck et al, 2004). The loss of semi-volatile compounds was found to play an important part in the difference between TEOM and Partisol (GLV) observed at a rural site in Harwell, UK, and one of the major particulate compounds lost was ammonium nitrate (NH_4NO_3) (Charron, 2004). It corresponded on average to about 26% of the material lost in the PM_{10} fraction and about 40% in the $PM_{2.5}$ fraction. The addition of ammonium nitrate mass detected in the gravimetric filter to the TEOM-PM_{10} data was found to improve the agreement between the TEOM and the gravimetric method (Charron et al, 2004; Hauck et al, 2004). It was observed that most of PM lost in the TEOM sampling system at Harwell belongs to the $PM_{2.5}$ fraction.

The fine particle fraction below 2.5 μm or even 1 μm found in Austria was always predominantly nitrate (Hauck et al, 2004). The ammonium and sulphate were also found accumulating in this fraction. Sometimes in the urban summer in Austria, most of nitrate was found in the coarse fraction. A similar trend of nitrate, ammonium, and sulphate in PM was also measured in southern Taiwan, where ammonium nitrate and ammonium sulphate ($(NH_4)_2SO_4$) were the major components of fine particles (Yuan, Lee, and Liu, 2000). Particulate sulphate, ammonium and nitrate are components of secondary PM, which are formed via photochemical reactions (APEG, 1999). Sulphate aerosol is formed from the oxidation of SO_2 emitted from burning of sulphur-contained fuel to sulphuric acid vapour, nucleating to form sulphuric acid droplets. The timescale for nucleation and accumulation processes of this particle fall into the regional or long-range transport scale. The highly acidic sulphate aerosol droplets can take up ammonia (NH_3) forming ammonium sulphate. The main source of ammonia is agriculture. Ammonium nitrate, nitric acid and nitrogen pentoxide are the main sinks of NO_x emissions from motor vehicle exhausts, and combustion from industry (APEG, 1999). About 33% by volume of emitted NO_x was estimated to convert to particulate nitrate in San Joaquin, California during the wintertime, and the particle equivalent of NO_x emissions was found to be on the order of 0.6 g of ammonium nitrate for each gramme of NO_x emission (Stockwell et al, 2000).

Table 5.23 BAM-PM_{10} and GHV-PM_{10} in Bangkok

Unit: $\mu g\ m^{-3}$

	BAM	GHV	GHV/BAM	BAM	GHV	GHV BAM
	Dindaeng			**Ramkhumhaeng**		
2001	45.8 ± 15.0	100.0 ± 36.7	2.2 ± 0.4	38.7 ± 13.9	56.2 ± 29.8	1.5 ± 0.6
Rainy	36.7 ± 8.3	76.1 ± 16.8	2.1 ± 0.4	27.9 ± 6.2	45.8 ± 19.6	1.7 ± 0.8
Winter	59.8 ± 11.9	137.2 ± 2.3	2.3 ± 0.5	45.2 ± 13.2	62.4 ± 33.6	1.3 ± 0.5
Summer	N/A	N/A	N/A	N/A	N/A	N/A
2002	47.8 ± 12.2	92.7 ± 35.8	1.9 ± 0.3	47.6 ± 13.0	49.3 ± 19.8	1.0 ± 0.3
Rainy	42.7 ± 10.1	75.4 ± 23.4	1.7 ± 0.2	46.6 ± 12.1	47.8 ± 18.0	1.0 ± 0.2
Winter	57.9 ± 11.8	122.2 ± 35.8	2.1 ± 0.3	50.0 ± 15.1	50.8 ± 24.9	1.0 ± 0.3
Summer	43.7 ± 8.1	85.2 ± 33.2	1.9 ± 0.3	44.8 ± 10.8	50.7 ± 11.2	1.2 ± 0.2
2003	49.3 ± 23.3	79.8 ± 22.1	1.8 ± 0.6	59.2 ± 16.0	51.5 ± 23.2	0.9 ± 0.2
Rainy	42.4 ± 15.2	71.1 ± 13.7	1.9 ± 0.7	54.0 ± 7.0	45.3 ± 14.2	0.8 ± 0.2
Winter	66.7 ± 15.8	117.0 ± 20.0	1.8 ± 0.4	87.9 ± 15.9	92.7 ± 17.2	1.1 ± 0.2
Summer	53.4 ± 35.0	78.9 ± 18.4	1.7 ± 0.5	51.9 ± 7.5	38.7 ± 7.6	0.7 ± 0.1
	Ladphrao			**Klong Jun**		
2001	35.3 ± 10.1	64.1 ± 29.7	1.8 ± 0.5	37.9 ± 15.7	58.5 ± 30.6	1.5 ± 0.5
Rainy	30.6 ± 3.8	56.4 ± 10.9	1.8 ± 0.3	28.7 ± 11.2	43.5 ± 27.2	1.5 ± 0.4
Winter	43.3 ± 12.5	77.4 ± 45.0	1.7 ± 0.7	47.6 ± 15.3	76.7 ± 30.9	1.7 ± 0.6
Summer	N/A	N/A	N/A	38.5 ± 15.8	53.7 ± 14.9	1.5 ± 0.3
2002	34.6 ± 9.7	60.9 ± 23.7	1.8 ± 0.5	43.2 ± 14.0	52.0 ± 25.9	1.2 ± 0.4
Rainy	31.1 ± 5.9	57.5 ± 21.3	1.8 ± 0.6	39.2 ± 11.0	46.1 ± 16.6	1.2 ± 0.3
Winter	39.2 ± 13.4	68.5 ± 29.4	1.8 ± 0.5	51.0 ± 17.5	62.4 ± 37.8	1.2 ± 0.5
Summer	35.0 ± 7.5	57.0 ± 18.4	1.7 ± 0.6	41.2 ± 11.1	51.3 ± 19.9	1.3 ± 0.5
2003	29.3 ± 6.5	65.9 ± 16.5	2.3 ± 0.5	40.7 ±12.3	47.7 ± 18.8	1.2 ± 0.3
Rainy	25.5 ± 3.1	61.3 ± 10.6	2.4 ± 0.5	34.3 ± 7.1	38.0 ± 9.5	1.1 ± 0.3
Winter	37.1 ± 6.7	81.9 ± 23.0	2.3 ± 0.7	56.0 ±13.2	72.2 ± 21.4	1.3 ± 0.2
Summer	32.6 ± 3.4	59.3 ± 8.4	1.8 ± 0.3	39.5 ± 7.2	45.0 ± 8.5	1.1 ± 0.1
	Thonburi Electricity			**Singharach**		
2001	58.0 ± 24.4	69.4 ± 30.6	1.2 ± 0.3	39.4 ± 14.6	62.9 ± 38.5	1.6 ± 0.7
Rainy	50.6 ± 10.3	58.8 ± 13.0	1.2 ± 0.2	32.7 ± 6.0	46.0 ± 18.6	1.4 ± 0.4
Winter	78.9 ± 37.6	92.1 ± 44.8	1.3 ± 0.4	53.0 ± 17.1	94.5 ± 47.7	1.8 ± 1.0
Summer	N/A	N/A	N/A	31.9 ± 8.6	51.2 ± 21.3	1.6 ± 0.5
2002	60.9 ± 25.9	63.1 ± 20.0	1.1 ± 0.2	51.5 ± 21.4	61.9 ±31.3	1.3 ± 0.7
Rainy	54.1 ± 16.3	57.4 ± 12.7	1.1 ± 0.2	46.5 ± 16.7	47.4 ± 18.1	1.1 ± 0.4
Winter	72.5 ± 37.0	74.1 ± 26.4	1.1 ± 0.2	65.5 ± 22.6	87.7 ±46.2	1.5 ± 1.1
Summer	59.6 ± 19.5	59.8 ± 17.9	1.1 ± 0.4	39.5 ± 16.7	49.6 ± 22.7	1.3 ± 0.4
2003	54.9 ± 20.4	59.8 ± 22.5	1.1 ± 0.3	56.4± 21.6	52.6 ± 30.5	0.9 ± 0.3
Rainy	45.0 ±10.0	47.7 ± 8.4	1.1 ± 0.3	45.1 ±8.3	37.3 ± 7.1	0.8 ± 0.2
Winter	73.5 ± 27.2	85.6 ± 28.6	1.2 ± 0.1	85.6 ± 17.5	94.3± 32.1	1.1 ± 0.4
Summer	56.0 ± 16.2	58.1 ± 13.5	1.1 ± 0.4	48.7 ± 16.1	40.2 ± 14.3	0.8 ± 0.2
				Nonsi		
2001				41.1 ± 14.5	58.8 ± 22.5	1.5 ± 0.4
Rainy				33.0 ± 12.3	44.1 ± 12.7	1.4 ± 0.4
Winter				50.4 ± 12.7	77.0 ± 21.7	1.6 ± 0.5
Summer				44.1 ± 10.6	63.3 ± 18.6	1.4 ± 0.1
2002				42.0 ± 13.8	60.4 ± 30.5	1.4 ± 0.4
Rainy				39.1 ± 11.2	48.8 ± 26.8	1.2 ± 0.4
Winter				49.5 ± 17.8	74.8 ± 33.7	1.5 ± 0.3
Summer				39.7 ± 10.1	66.8 ± 24.7	1.7 ± 0.5
2003				41.5 ± 15.0	57.5 ± 23.2	1.4 ± 0.4
Rainy				35.0 ±7.1	44.4 ± 10.4	1.3 ± 0.3
Winter				55.4 ± 19.7	83.7 ± 24.9	1.6 ± 0.5
Summer				37.2 ± 6.2	51.1 ± 4.9	1.4 ± 0.3

The conversion reaction of NO_x to particulate nitrate is undertaken in a relatively rapid series of day-time and night-time reactions (APEG. 1999). From the literature review, it seems to show that both of ammonium sulphate and ammonium nitrate particulates can be found in rural and urban areas. However, the latter may be higher near to the roadside sites, as road traffic is the main source of NO_x and its formation timescale is relatively rapid on a daily basis.

This assumption was confirmed by some studies on chemical composition of PM_{10} and $PM_{2.5}$ at one roadside, two urban background, and two regional background sites in Germany. The results indicated that nitrate particulate at the roadside (4.6 $\mu g/m^3$ in PM_{10} and 4.3 $\mu g/m^3$ in $PM_{2.5}$) was greater than that found at urban background sites (4.3 - 4.4 $\mu g/m^3$ in PM_{10} and 3.3 - 3.7 $\mu g/m^3$ in $PM_{2.5}$) and regional background sites (2.4 - 3.0 $\mu g/m^3$ in PM_{10} and 2.2 $\mu g/m^3$ in $PM_{2.5}$) (Lenschow et al, 2001). Very high nitrate particulate around 10.6 $\mu g/m^3$ was found in the GHV-TSP at Dindaeng roadside station, Bangkok in January 2002 (winter); and low levels of 1.4 $\mu g/m^3$ could be observed in August 2001 (rainy season) (Kato et al, 2004). Unfortunately, the number of nitrate particulate and other semi-volatile compounds in PM within different size ranges as a long-term average in Bangkok is not known. Similar trends to the observations in Germany were also found elsewhere, e.g. Macao, China (Wu et al, 2003), Hong Kong (Ho et al, 2003), Spain (Querol et al, 2004). Hence, it assumed that the amount of nitrate particulate at roadside sites is probably greater than that at urban background sites. The loss of nitrate particle in the BAM sampling system at roadside sites should be higher than that in BAM at background sites. The GHV/BAM ratio at the roadside sites should be higher than that at the urban background sites. This conclusion can provide a reason for the higher GHV/BAM ratio found at the roadside sites in Bangkok (excluding Thonburi Electricity station) as seen from Figure 5.13. The figure shows that the difference between GHV-PM_{10} and BAM-PM_{10} at roadside and urban background sites is about 90% and 30% respectively. The results agree with the assumption above. Thus the correction factor for assessing GHV-PM_{10} applied to the roadside and urban background sites should be different. This conclusion agrees with the suggestion to incorporate the geographical variability in the correction factor (Green, Fuller, and Barratt, 2001).

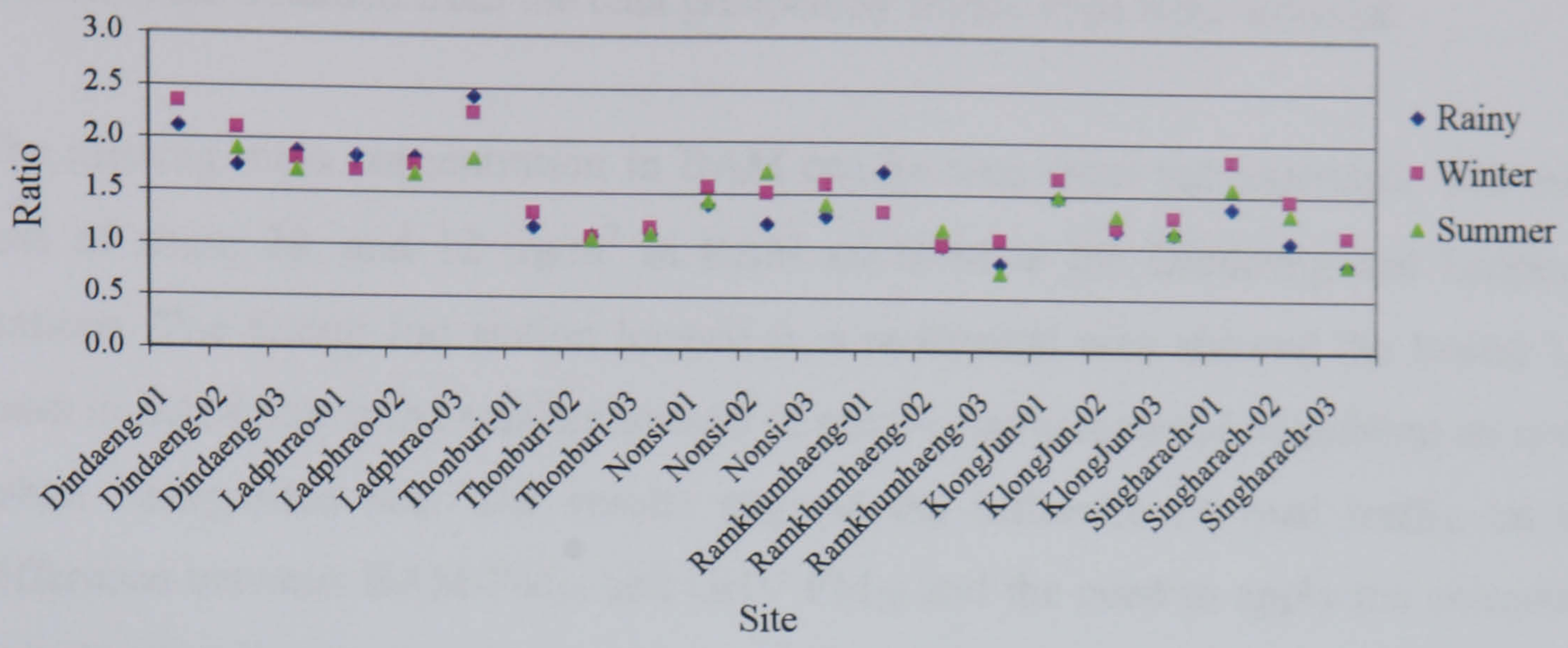


Figure 5.13 GHV/BAM ratio in Bangkok

In Bangkok, the highest average PM_{10} levels were always observed in the winter and the lowest in rainy seasons. However, the ratios of GHV/BAM indicate uncertain seasonal patterns. Although several fractions in winter showed highest values, in general there was little contrast between the seasons. Thus, the temporal variability of GHV/BAM as previously recommended can be negligible in Bangkok. This conclusion, then, disagrees with the observation in Austria, in which the GHV and BAM showed clear seasonal patterns between summer and winter (Hauck et al, 2004). The agreement was better during the summer than the winter, whilst in Bangkok a better agreement between the two methods did not always occur in the summer.

The best fitting curves for the BAM-GHV relationships were linear. The linear regression equations and R-square values (R^2) of the relationships between BAM-PM_{10} and GHV-PM_{10} at all sites are depicted in Table 5.24. In general, R^2 of all relationships show weak correlation because of the scattered data. However, all data show a clear trend as seen in Figures 5.14. When the regression was conducted in groups of locations such as the roadside sites (excluding Thonburi Electricity) and the urban background sites, rather than the mixing all types, the relationships were improved. The R^2 of the stations rose from 0.3384 to 0.5091, and 0.4124 at the roadside and urban background stations respectively. The R^2 of data grouped into station type was found higher than the R^2 at the Dindaeng and Ladphrao stations and two urban background stations; Ramkhumhaeng and Singharach, but not for Klong Jun and Nonsi stations, where individual R^2 rose to 0.4856 and 0.5206. However they

were in a similar range of R^2 to the urban background stations. Hence, the relationships obtained from the data grouped by station type were selected.

The missing mass concentration in BAM can be seen from the intercepts. The mass loss of about 28, and 12 $\mu g/m^3$ in BAM occurred at the Dindaeng and Ladphrao stations. The Klong Jun station located in a residential area showed the lowest lost mass in BAM due to the smaller amount of semi-volatile material in ambient air at the urban background site. The results suggest the influence of road traffic on the difference between BAM-PM_{10} and GHV-PM_{10} and the need to apply the correction factors according to the geographical conditions. The equations for the all stations, roadside station and urban background stations were also conducted assuming a zero-intercept as seen in Table 5.24 and the R^2 of equations with and without the intercept can be compared. Hence for simplicity in practice, the equations with zero-intercept were selected for assessing GHV-PM_{10}. However, these equations are recommended to apply under the conditions that BAM-PM_{10} will not equal to zero. If BAM-PM_{10} is zero, the equations with the intercept should be used. From the results, then, the correction factor for the roadside and urban background sites were 1.85 and 1.23 respectively. For obtaining the regional background PM_{10} as measured by the GHV, the correction factor of 1.23 was applied to 30 $\mu g/m^3$. Then the regional background GHV-PM_{10} for Bangkok is estimated to be about 37 $\mu g/m^3$.

Table 5.24 Regression equation of the relationship between BAM-PM_{10} and GHV-PM_{10} at monitoring sites

Station	Equation	R^2
Dindaeng	y = 1.2978x + 28.384	0.4277
Ladphrao	y = 1.5561x + 11.628	0.3813
Thonburi Electrcity	y = 0.7979x + 16.737	0.6705
Ramkhumhaeng	y = 0.9238x + 7.1745	0.3818
Klong Jun	y = 1.2631x + 0.8121	0.4856
Singharach	y = 1.0649x + 6.7693	0.3906
Nonsi	y = 1.3006x + 4.8832	0.5206
All stations	y = 0.9492x + 19.693	0.3384
	y = 1.3232x	0.2773
Roadside	y = 1.4749x + 17.064	0.5091
	y = 1.845x	0.4725
Urban background	y = 1.0804x + 7.7608	0.4124
	y = 1.2331x	0.4035

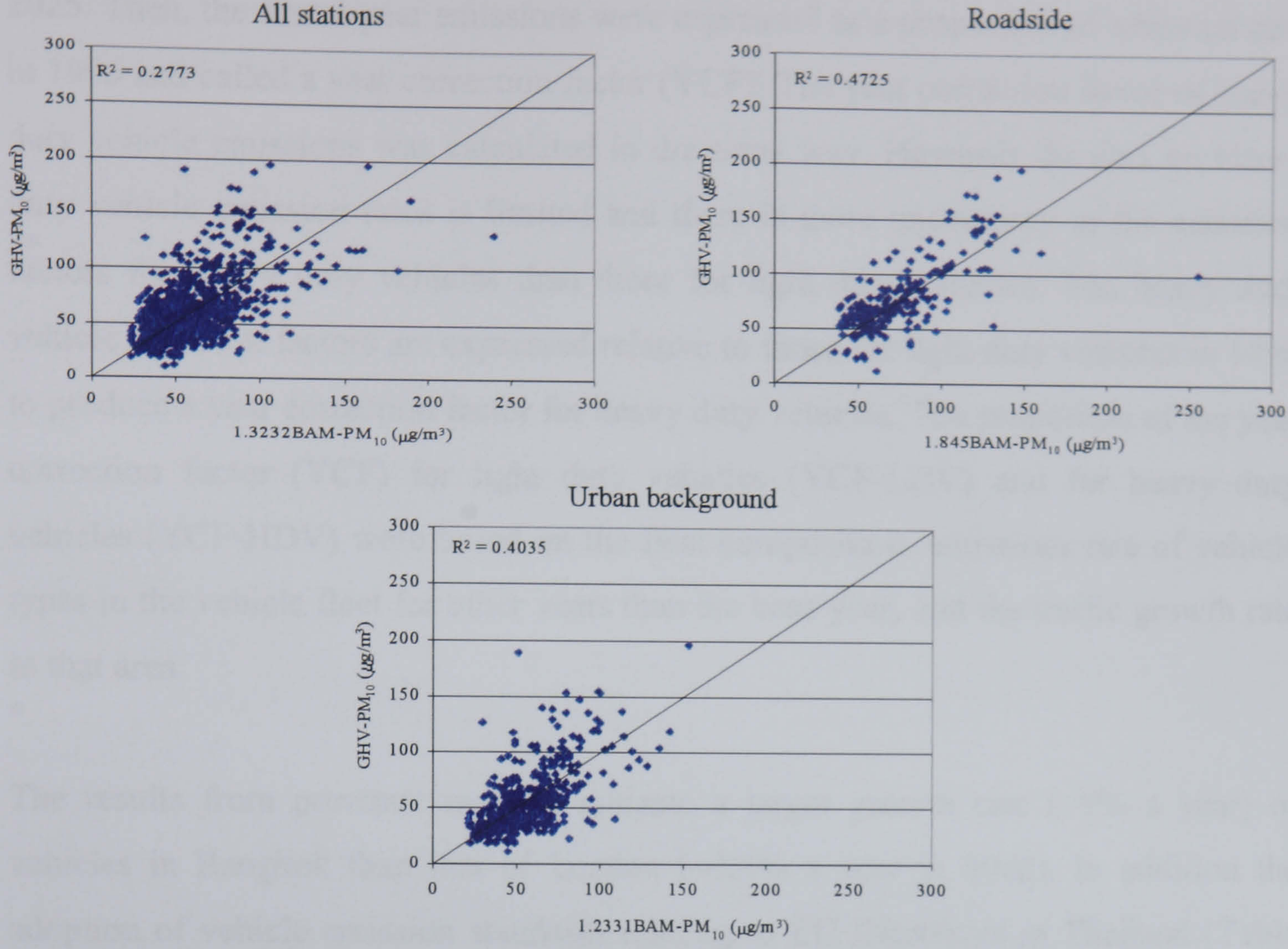


Figure 5.14 Relationship between BAM-PM_{10} and GHV-PM_{10} in Bangkok during 2001-2003

5.8 Year Correction Factor (YCF)

The Year Correction Factor (YCF) is a factor used in the GRAM model for predicting rate of emission changes in future years against the base year (1996). It is employed in predicting the effective light duty vehicle (LDV) and heavy duty vehicle (HDV) emissions in the year to be modelled, and in estimating the urban emission factor change for the urban background dispersion model as shown in shading in Figure 5.15.

The year correction factor (YCF) was adopted from the Highways Agency's DMRB approach. This factor was developed from the change of vehicle emission standards regulated in the UK in combination with the fleet composition and the growth rate of vehicle in types (Highways Agency, 1999). A function was assigned to each of the categories of vehicle considered distinctive in terms of their emission properties, giving typical rates of emission as a function of its average speed. These functions were then combined with reference to the fleet composition model to provide a composite function for the light duty vehicle fleet for each year between 1996 and

2025. Then, the future year emissions were expressed as a proportion of emission rate in 1996 and called a year correction factor (YCF). The year correction factor of heavy duty vehicle emissions was calculated in the same way. However the data on heavy duty vehicle emission rates is limited and there is more uncertainty in the emission factors for heavy duty vehicles than those for light duty vehicles. The heavy duty vehicle emission factors are expressed relative to those for light duty vehicles in 1996 to produce a year correction factor for heavy duty vehicles. The proportion of the year correction factor (YCF) for light duty vehicles (YCF-LDV) and for heavy duty vehicles (YCF-HDV) were based on the fleet composition, emissions rate of vehicle types in the vehicle fleet for other years than the base year, and the traffic growth rate in that area.

The results from previous sections indicate a larger growth rate (~9% a year) of vehicles in Bangkok than that of London (~0.4% a year in 2002). In addition the adoption of vehicle emission standards relating to EU Directives in Thailand (Table 5.25) were different. For example, the 88/76/EEC Directive implemented in Thailand during 30 March 1995 – 23 March 1996 was not implemented in the UK and some EU directives, e.g. 83/351/EEC and 88/77/EEC were implemented in the UK but not in Thailand. Moreover, the implementation date of the same EU Directives in Thailand was later than the date applied in the UK, for example, the 96/69/EEC in the UK was introduced to new petrol and diesel vehicles of engine size <1251 kg on October 1, 1997 and for engines >1251 kg on October 1, 1998 (Highways Agency, 2003), whilst the same directive was applied to both light duty petrol cars and light duty diesel vehicles in Thailand on August 25, 2001. Hence, it was assumed that the year correction factors of the two cities were different.

As mentioned above that the year correction factor is based on the fleet composition, emission rate of vehicle types in fleet beyond the base year, and traffic growth rates in that area. Hence, the trends and composition of vehicles in Bangkok during 1996-2025, and the emission rates and their fraction were studied in a preliminary stage. Due to the differences of application of EU Directives in the UK and Thailand, the DMRB method and EU Directives' limit values method were compared so as to know how they affected estimations of the year correction factor. From the results in this step, the EU Directives' limit values method was chosen for predicting the year

correction factor of Bangkok because the two methods give the similar results and the EU Directives' limit values method can apply to all the EU Directives implemented in Thailand, while the DMRB method can apply to some of the EU Directives used in Thailand. The study also covered the emission conversion factor. This factor is used for calculating the emission of a pollutant for a light duty vehicle in the base year in the GRAM model.

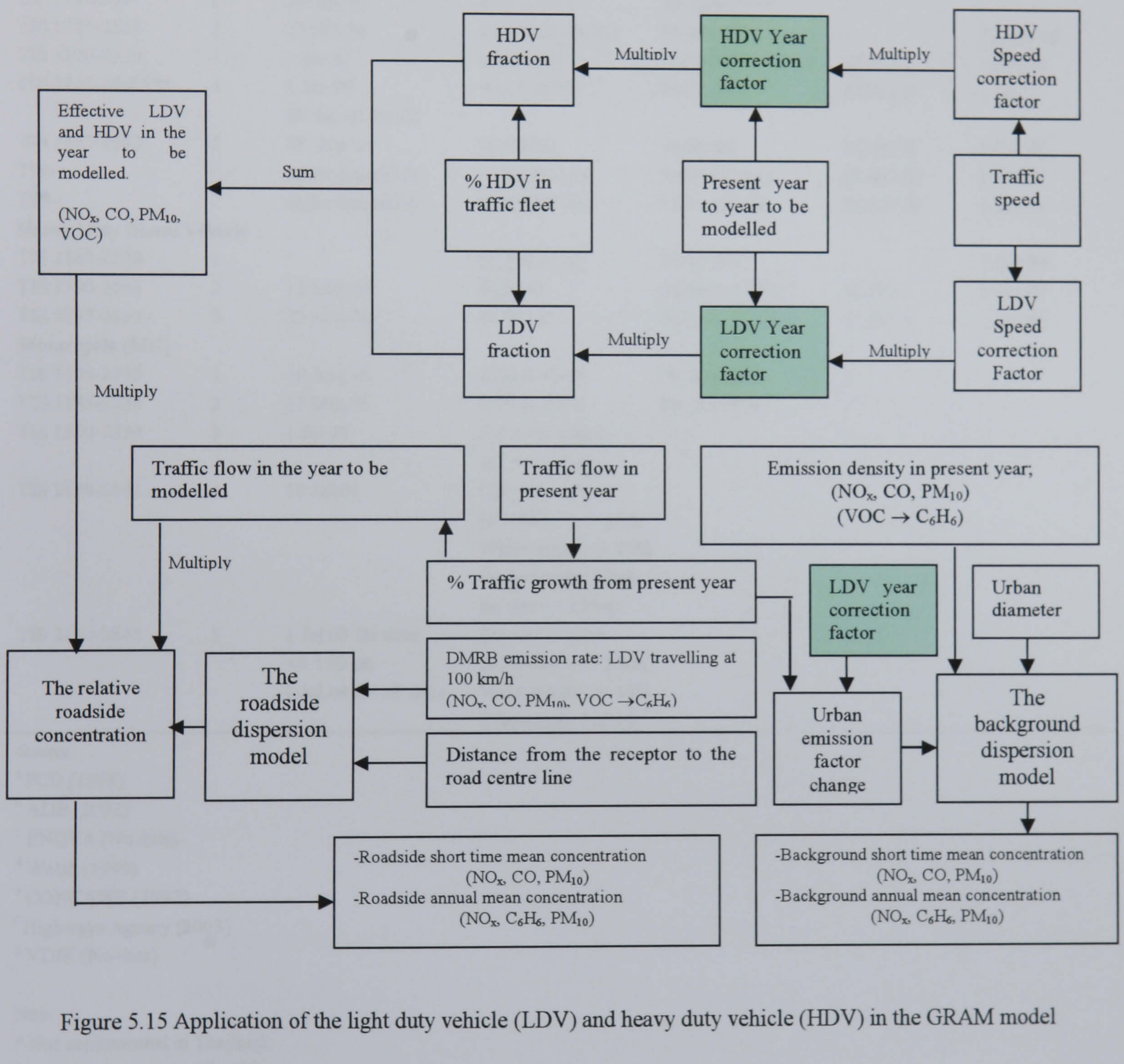


Figure 5.15 Application of the light duty vehicle (LDV) and heavy duty vehicle (HDV) in the GRAM model

Table 5.25 Emission Standards which new vehicle in Thailand must comply

Thai Standard[a, b]	Level	Implementation date in Thailand	Reference standard[a, b]	Equivalent EU Directive[c, d, e]	EURO standard[f, g]	Implementation date in UK[f]
Light Duty Petrol Vehicle						
TIS 1085-2535	1	*	ECE R15-04	83/351/EEC	-	1 Oct 86
TIS 1120-2535	2	30 Mar 95	ECE R83-B	88/76/EEC**	-	-
TIS 1280-2538	3	24 Mar 96	ECE R83-01(B)	91/441/EEC	-	31 Dec 92
TIS 1365-2539	4	1 Jan 97	93/59/EEC	93/59/EEC	EURO I	1 Oct 94
TIS 1440-2540***	5	1 Jan 99	94/12/EC***	94/12/EC***	EURO II***	1 Jan 97
TIS 1870-2542	6	25 Aug 01	96/69/EC	96/69/EC	EURO II	1 Oct 97
TIS--	7	under discussion	98/69/EC (A)	98/69/EC (A)	EURO III	1 Jan 01
TIS--	8	under discussion	98/69/EC (B)	98/69/EC (B)	EURO IV	1 Jan 06
Light Duty Diesel Vehicle						
TIS 114-2536	1	29 Jan 95	ECE R 83-C	88/76/EEC**	-	-
TIS 1285-2538	2	23 Feb 96	ECE R 83-01 (C)	91/441/EEC	-	31 Dec 92
TIS 1370-2539	3	1 Jan 97	93/59/EEC	93/59/EEC	EURO I	1 Oct 94
TIS 1435-2540***	4	1 Jan 99 30 Sep 01 for DI	94/12/EC***	94/12/EC***	EURO II	1 Jan 97
TIS 1875-2542	5	25 Aug 01	96/69/EC	96/69/EC	EURO II	1 Oct 97
TIS--	6	under discussion	98/69/EC (A)	98/69/EC (A)	EURO III	1 Jan 01
TIS--	7	under discussion	98/69/EC (B)	98/69/EC (B)	EURO IV	1 Jan 06
Heavy Duty Diesel Vehicle						
TIS 1180-2538	1	*	ECE R 49-01	88/77/EEC	-	1 Oct 90
TIS 1290-2538	2	12 May 98	EURO I	91/542 (A)/EEC	EURO I	1 Oct 93
TIS 1295-2541	3	23 May 00	EURO II	91/542 (B)/EEC	EURO II	1 Oct 96
Motorcycle (MC)						
TIS 1105-2535	1	10 Aug 93	ECE R 40-00	No directive	-	-
TIS 1185-2536	2	15 Mar 95	ECE R 40-01	No directive	-	-
TIS 1360-2539	3	1 Jul 97	CO <=13 g/km HC <= 5 g/km	-	-	-
TIS 1650-2541	4	30 Jul 01	CO <=4.5 g/km HC+NOx <= 3 g/km White smoke <= 15% Evaporative 2 g/test for size >= 150 cc	-	-	-
TIS 2130-2545	5	1 Jul 03 for sizes <= 110 cc 1 Jul 04 for all sizes	CO <=3.5 g/km HC+NOx <= 2 g/km White smoke <= 15% Evaporative 2 g/test	-	-	-

Source:
[a] PCD (1998)
[b] ADB (2003)
[c] ENGVA (No date)
[d] Walsh (1999)
[e] CONCAWE (1997)
[f] Highways Agency (2003)
[g] VDIK (No date)

Note
* Not implemented in Thailand
** Not implemented in the UK
*** The 94/12/EC standard applies only to vehicle <= 6 seats, vehicle > 6 seats follows 93/59/EEC standards

5.8.1 Bangkok vehicle: trend and composition between 1996 and 2025

Road vehicles in Thailand are registered under three Acts: the Motor Vehicle Act, the Land Transport Act, and the Non-Motorised Vehicle Act (Department of Land Transport, 1999). The vehicles under the last act were not included in this research as they do not contain an engine. The classification of vehicles in the two former acts was re-classified to main vehicle types and grouped to Light Duty Vehicle (LDV) and Heavy Duty Vehicle (HDV) in Table 5.26.

Table 5.26 Classification of light duty vehicle (LDV) and heavy duty vehicle (HDV) in Thailand

Act	Sub-type	Main type	LDV-HDV type
Motor Vehicle Act	Sedan	Car	LDV
	Urban Taxi		
	Interprovincial Taxi		
	Fixed route Taxi		
	Hotel Taxi		
	Tour taxi		
	Car for hire		
	Van and Pick up	Van and Pick up	
	Microbus and		
	Passenger pick up		
	Motorcycle	Motorcycle	
	Motortricycle	Other	
	Motortricycle Taxi		
	Tractor		
	Road roller		
	Farm's vehicle		
	Automobile's Trailer		
Land Transport Act	Fixed route Bus	Bus	HDV
	Non-fixed route Bus		
	Private Bus		
	Small Rural Bus		
	Non-fixed route Truck	Truck	
	Private Truck		

To estimate the year correction factor of the light duty vehicle and heavy duty vehicle (YCF-LCD and YCF-HDV) during 1996 - 2025, the number of vehicles and their composition in Bangkok were predicted. The traffic growth rate in Bangkok during 1989-2002 in a previous section shows that the vehicle number in 1989 was 1.72 million, the number reached 5.48 million in 2003. The average growth rate between 1990 and 1994 was over than 11% and dropped to around 9% during 1995-1997. After 1998, the growth was dropped due to economic crisis between 1998 and 1999. If the business was as usual, it seems the traffic average growth rate during 1995-1999

would be 9%. Then it might be reasonable to assume that the traffic growth rate would decrease about 2% over a period of five years.

From Table 5.2, the 'Car' category occupied around 30% of total numbers, and 20% were in a group of 'Van and Pick-Up'. The 'Microbus' and 'Passenger pick up' category was also categorized in the latter group. The 30%-70% in the group of 'Van and Pick-Up' were vehicles with less than 6 seats (MOTC, 1999; Department of Land Transport, 2003). In Thailand, the 'Light duty petrol vehicle' and the 'Light duty diesel vehicle' are registered in the groups of 'Car' and 'Van and Pick up' respectively. Pick-up is popular for families as well as 'Car' due to the relative inexpensiveness of the vehicle and fuel compared to the 'Car' category. The Motorcycle (MC) category is around 40%, the biggest share in Bangkok vehicle's fleet. The motorcycle is the first choice of low-income families and a favorite vehicle for young people. Motorcycles often serve as a stepping-stone to car ownership (World Resource Institute, 1996). They are smaller and easier to park, and can cut a path through congested roads (Kenworthy, 1995). Motorcycles did not play an important part in London. They represent only 2% of London's vehicle fleet (Department of Transport, 1995). More than 80% of vehicles (~1.9 million vehicles) in London would be classified as falling into the 'Car' category (Department of Transport, 1995).

A previous study on vehicle ownership in American, Australian, European and Asian cities found that the vehicle ownership varied considerably in cities around the world (Kenworthy, 1995). For example, in 1993, the wealthier regions like United States and the member countries of the Organization for the Economic Co-Operation and Development (OECD) owned 561 and 366 car per 1000 residents (World Resource Institute, 1996). The vehicle and car ownership per 1000 population was higher in an urban area such as the San Francisco Bay area, USA in 1995, these figures were 729, and 592 respectively (Purvis, 1996). The car ownership in the counties of San Mateo and Marin located in this area was up to 742, and 705 respectively. The car ownership per 1000 population in London in 1998 was 363 (DETR, 2000b) and traffic growth was about 2% between 1989 and 1999 (DETR, 2000b). The growth rate in 2002 was only 0.4% (DfT, 2002). It seems that the vehicle population in London has reached saturation for a number of years. In 1998, the vehicle ownership and car ownership

per 1000 people in Bangkok was around 710 and 225 (BMA. 1999a. 2002). Previously in 2002, the vehicle ownership and car ownership per 1000 people in Bangkok were about 934, and 293 respectively. Comparing car ownership in cities elsewhere, this figure in Bangkok seems to have a room to grow.

It is a social value in Thailand that most people have high regard for cars as a wealth symbol (Rujopakarn, 2003). They want to have a 'Car' or 'Van/Pick-up' for themselves or their families due to poor public transport conditions and for the freedom of travelling. A transport survey in Bangkok Metropolitan Region (BMR) in 2001 (Rujopakarn, 2003) indicated that there were about 22 million person trips per day (excluding 4 million truck trips per day), of which 57% were private trips. even though there was already a mass rapid transit line in operation. The study concluded that it was due to the poor public transport services, rising personal incomes and increasing car ownership, but a major contributing factor was the greater private transport accessibility. The ease of travel by private transport was four times higher than by public transport. Not only were these social and economic factors the driving force of the growth in vehicle ownership in Thailand, but also there was a political factor, due to Thai government's support of the automobile industry as an important generator of economic growth. All of these driving forces associated with the lower car ownership than those of developed countries suggest the probability of greater car ownership in Bangkok in future.

Regarding several factors promoting the growth of vehicle ownership mentioned above, it was assumed that if the present growth rate of 9% a year was to continue through to 2005, the car ownership per 1000 residents would be about 365, and the vehicle number would be around 7 million which is close to the population numbers at that time (BMA, 2002). Then it was expected that the vehicle growth rate should start reducing. The record of 2% growth rate reduction was applied over every five-year period after 2006, leading to a growth rate after 2020 of 1% a year. The same composition as the present time was assumed. The trend and composition of Bangkok vehicles between 1996 and 2025 were estimated under this assumption.

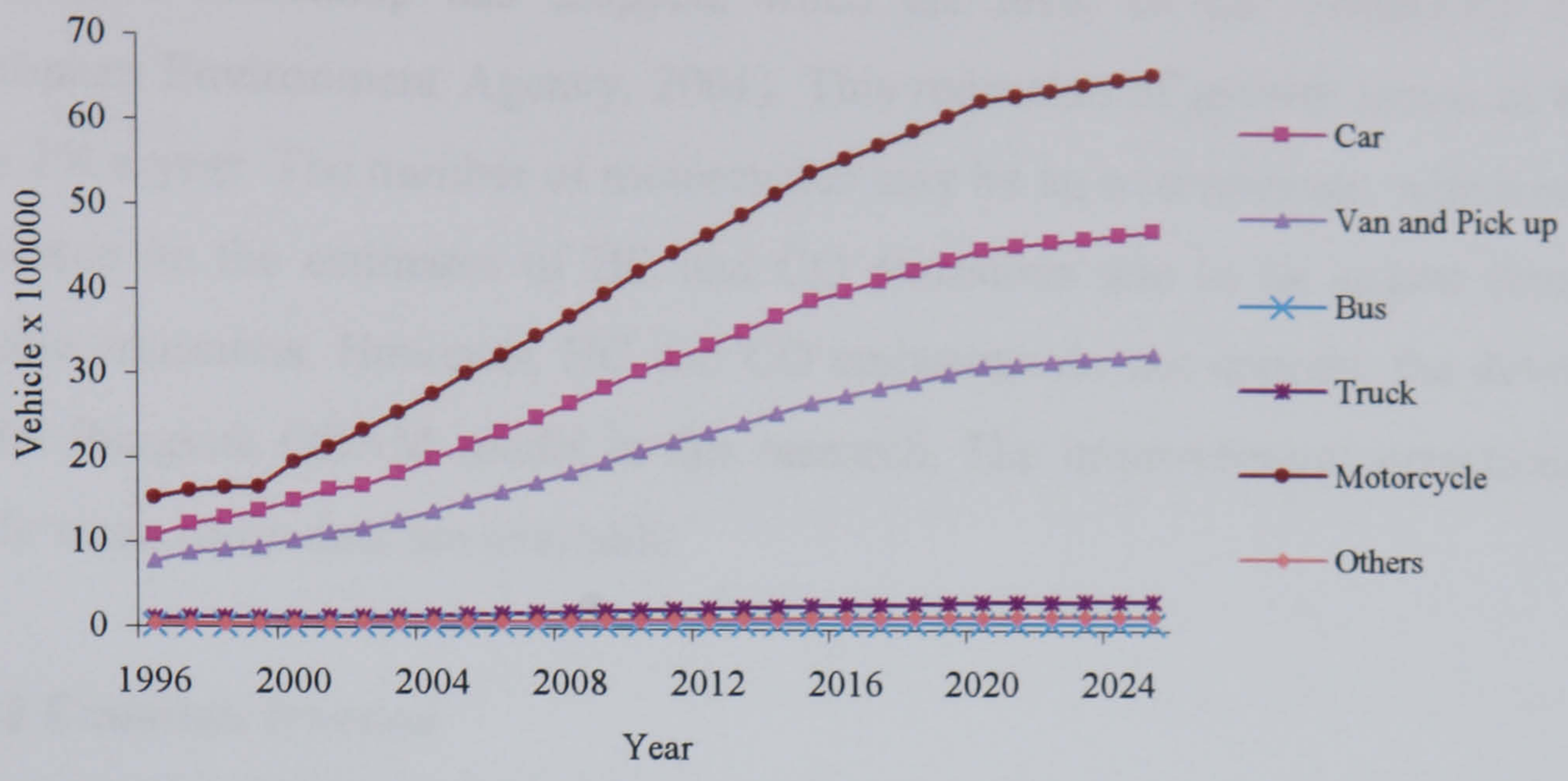


Figure 5.16 Tren of vehicle population in Bangkok

Numbers and composition of vehicles during 1996-2002 in Figure 5.16 were from records, and both beyond 2002 are from predicted figures. Similarly the composition since 2003 is based on the same composition as found in records. The total number of vehicles in Bangkok will be around 7 million in 2005, when the car ownership is 365 per 1000 persons. The figure of car ownership in this year is similar to the figure in London and the Organization for the Economic Co-Operation and Development (OECD), but it was just two thirds of that in San Francisco, and half of the figures of San Monteo and Marin. After that, a 2% reduction in every five years was applied, the vehicle population seems to reach saturation point after 2020 with the number of 14.5 million. By that time, car ownership in Bangkok will be around 650 per 1000 residents or around 7 million vehicles, and the motorcycle ownership will be approximately 6 million.

However, uncertainty will exist in the trend after 2005, if the reduction of vehicle growth rate is more than 2% every five years, due to a greater change of travel mode from private to public mass transport. The uncertainty in this estimate will be a factor leading to an overestimate in the year correction factor after 2005. Nonetheless, the probability of the trend is reasonable for car ownership due to the several support factors existing in Thai society as mentioned previously. Compared to elsewhere, the figure of 650 per 1000 person in 2020 from the estimate is less than the recorded figure at San Mateo and Marin counties in San Francisco in 1995.

For motorcycles, investigations in EU countries during 1980-2010 found that motorcycle ownership has dropped, when the level of car ownership has risen (European Environment Agency, 2001). This reduction of growth seems to be larger than 2% a year. The number of motorcycles may be an overestimate, which will be an influence on the estimates of HC and CO emissions due to its largest share in the vehicle emissions. However, HC and CO emissions do not concern the development of the Bangkok GRAM model in this research. The improvement/corrections can be made when more data are available.

5.8.2 Emission fraction

The total number of each vehicle type from the previous section was distributed to obtain the vehicle fractions under the relevant emission standards in each year between 1996 (base year) and 2025. The Directive 98/69/EC (A) or EURO III and 98/69/EC (B) or EURO IV were assumed to be implemented in Thailand on 1 January 2004 and 1 January 2006 respectively and from 1 January 2006-2025, emission rates from new LDV and HDV vehicles were assumed under the Directive 98/69/EC (B) or EURO IV. An example is shown in Table 5.27.

Table 5.27 Example of the vehicle fraction of 'Car' under standards

Thai Standard	Implemented period	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
TIS 1085-2535	Pre-30 Mar 95	0.877	0.784	0.735	0.687	0.631	0.578	0.560	0.514	0.472	0.433
TIS 1120-2535	30 Mar 95-23 Mar 96	0.061	0.054	0.051	0.048	0.044	0.040	0.039	0.036	0.033	0.030
TIS 1280-2538	24 Mar-31 Dec 96	0.063	0.056	0.053	0.049	0.045	0.041	0.040	0.037	0.034	0.031
TIS 1365-2539	1 Jan 97 - 31 Dec 98		0.105	0.161	0.151	0.138	0.127	0.123	0.113	0.103	0.095
TIS 1440-2540	1 Jan 99 - 24 Aug 01				0.065	0.143	0.186	0.180	0.165	0.152	0.139
TIS 1870-2542	25 Aug 01 - 31 Dec 03						0.028	0.058	0.136	0.125	0.114
TIS-- (a)	1 Jan 04 - 31 Dec 05									0.083	0.158
TIS--(b)	1 Jan 06 - 31 Dec xx										
		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

(a) = the dircetive 98/69/EC (A) was assumed

(b) = the directive 98/69/EC (B) was assumed

The vehicle fractions under emission standards obtained from the previous section, were then multiplied by their corresponding emission standard to give the emission fraction of that emission standard, and then summed over all emission fractions in each year to calculate the proportion during the years 1996 – 2025 compared with 1996. The average year correction factors of the 'Car', 'Van and Pick up', and 'Motorcycle' categories were taken for the year correction factors of light duty vehicles (YCF-LDV), and the correction factors of the 'Bus' and 'Truck' categories were taken to be the year correction factors of the heavy duty vehicles (YCF-HDV).

The vehicles in the group of 'other' as shown in Table 5.2 were excluded due to their unknown emissions and their share, which was less than 1%.

5.8.3 DMRB method and EU Directives' limit values method

Due to the differences of the emission standards introduced to motor vehicles in the UK and Thailand as mentioned previously, the year correction factor estimated from the DMRB method (hereinafter called as 'Method 1') and the calculation based on the relating EU Directives' limit values (hereinafter called as 'Method 2') were then compared to see whether Method 2 could act as a surrogate for the Method 1, because some of the DMRB's coefficients for the directive that were not implemented in the UK were not available. The test was estimated under the following assumptions and NO_x emissions were chosen for this purpose.

1. The year correction factor for light duty vehicle (YCF-LDV) was based on light duty petrol vehicles and light duty diesel vehicles only. Motorcycles were not included because the new emission standards for motorcycle in Thailand after 1997 were adopted from Taiwan, and the NO_x coefficients are not available from the DMRB method. Thus it was not possible to estimate NO_x emission rates of motorcycles in Bangkok by the DMRB method.

2. As the Directive 88/76/EEC was implemented in Thailand between 30 March 1995 and 23 March 1996, but not implemented in the UK, the DMRB's coefficient for this directive was not available (Highways Agency, 1999). The total number vehicles in Bangkok grew over that period by about 300,000 vehicles. This study, then, obtained the coefficient of the Directive 83/351/EEC, a previous directive, for finding the emission rate for the light duty vehicles over that period.

3. In practice, the light duty diesel vehicle in Thailand is registered in two subgroups of 'Van and Pick up' and 'Microbus and Passenger pick up'. Nearly all of the former subgroup have <= 6 seats. In this research they were grouped in the 'Van and pick up' type. The Directive 94/12/EC under TIS 1440-2540 (for petrol vehicle) and TIS 1435-2540 (for diesel vehicle) was applied to the vehicle <= 6 seats only. The vehicles with >6 seats were regulated under the Directive 93/59/EEC in class N1+N3. In Bangkok, most of light duty petrol vehicles are in class <= 6 seats, so the Directive 94/12/EC was used for all light duty petrol vehicles. The light duty diesel vehicles <= 6 seats shared about 30-70% of this vehicle type (MOTC, 1999; Department of Land

Transport, 2003). Thus 50% of light duty diesel vehicles were assumed under the Directive 94/12/EC and the rest of them followed the Directive 93/59 EEC.

4. The rest of Thai standards correspond to the relevant EU Directives.

5. The emission rate calculated under the DMRB method was obtained from the vehicle speeds of 100 km/h.

6. When there were more than one emission rates from a Directive due to different engine sizes, all emission rates were averaged.

7. The Directive 98/69/EC (A) or EURO III and 98/69/EC (B) or EURO IV was assumed to be implemented in Thailand on 1 January 2004, and 1 January 2006 respectively.

8. From 1 January 2006 - 2025, emission rates from new light duty vehicles (LDV) and heavy duty vehicle (HDV) vehicles were assumed under the Directive 98/69/EC (B) or EURO IV.

Examples of applying Methods 1 and 2 are shown in Tables 5.28 and 5.29. Each method had its specific assumption as the following.

Assumption of Method 1

(1) The vehicles pre-1997 emit NO_x following the 83/351 standard.

(2) As the ECE R83-B or the Directive 88/76/EEC was not implemented in the UK, the emission rate was obtained from the previous Directive 83/351/EEC.

(3) When the category of engine size is unknown, the average emission rates from the three engine sizes are used. This method was also used for all vehicles.

(4) Emissions under a standard were calculated from the product of vehicle fraction, and average emission of that category.

Assumption of Method 2

The estimate was based on the limit values regulated in the legislation. For the NO_x, the limit value of $HC+NO_x$ was used. HC and NO_x are in combination in most Directives and without identification of NO_x fraction.

Table 5.28 Example of the calculation of YCF-Car-NO_x-Method 1

Thai Standard	EU legislation	Engine size	E (g/km) at 100 km/hr	Ave. emission rate (g/km)	1996	1997	1998
TIS 1085-2535	ECE R15-04	<1.4	2.513	3.020	2.648	2.369	2.221
		1.4-2.01	3.153				
		>2.01	3.395				
TIS 1120-2535	ECE R83-B	<1.4	2.513	3.020	0.183	0.164	0.154
		1.4-2.01	3.153				
		>2.01	3.395				
TIS 1280-2538	ECE R83-01(B)	<1.4	0.493	0.439	0.028	0.025	0.023
		1.4-2.01	0.436				
		>2.01	0.3882				
TIS 1365-2539	93/59/EEC	small-large	0.457	0.457		0.048	0.074
TIS 1440-2540***	94/12/EC	<1.4	0.2167	0.193			
		1.4-2.01	0.192				
		>2.01	0.1701				
TIS 1870-2542	96/69/EC	small-large	0.2326	0.233			
TIS--	98/69/EC (A)	<1.4	0.13022	0.116			
		1.4-2.01	0.115				
		>2.01	0.10205				
TIS--	98/69/EC (B)	<1.4	0.06888	0.062			
		1.4-2.01	0.0613				
		>2.01	0.05465				
			Total emission		2.858	2.605	2.471
			Fraction		1.000	0.912	0.865

*** The application of the Directive 94/12/EC in Thailand incorporates the Directive 93/59/EEC for "Car" more than 6 seats. In Bangkok, most of the "Car" are less than 6 seats. Thus, the emission rate of the Directive 93/59/EEC under TIS 1440-2540 was not applied to the "Car"

Table 5.29 Example of the calculation of YCF-Car-NO_x-Method 2

Thai Standard	EU legislation	Engine size	E (g/km)	Ave. emission rate (g/km)	1996	1997	1998
TIS 1085-2535	ECE R15-04	<751->1250 kg	4.69-6.91	5.80	5.085	4.550	4.265
TIS 1120-2535	ECE R83-B	<1400 cc	3.7	2.43	0.147	0.132	0.124
		1400-2000 cc	2.0				
		>2000 cc	1.6				
TIS 1280-2538	ECE R83-01(B)	all	0.97	0.97	0.061	0.054	0.051
TIS 1365-2539	93/59/EEC	< 1251 kg	0.97	1.36		0.143	0.219
		1250-1700 kg	1.4				
		> 1700 kg	1.7				
TIS 1440-2540***	94/12/EC	all	0.5	0.50			
TIS 1870-2542	96/69/EC	< 1251 kg	0.5	0.60			
		1250-1700 kg	0.6				
		> 1700 kg	0.7				
TIS--	98/69/EC (A)	all	0.35	0.35			
TIS--	98/69/EC (B)	all	0.18	0.18			
			Total emission		5.293	4.879	4.659
			Fraction		1.000	0.922	0.880

*** The application of the Directive 94/12/EC in Thailand incorporates the Directive 93/59/EEC for "Car" more than 6 seats. In Bangkok, most of the "Car" are less than 6 seats. Thus, the emission rate of the Directive 93/59/EEC under TIS 1440-2540 was not applied to the "Car"

The results as illustrated in Figure 5.17 show that Method 1 and Method 2 gave similar estimates. Even though, the total emissions between two methods over the period of 1996-2025 are different, the rates of emission change are similar. Thus, Method 2 was selected for further study of the year correction factor for light duty vehicles (YFC-LDV) and correction factor for heavy duty vehicles (YCF-HDV) of CO, NO_x, HC, and PM.

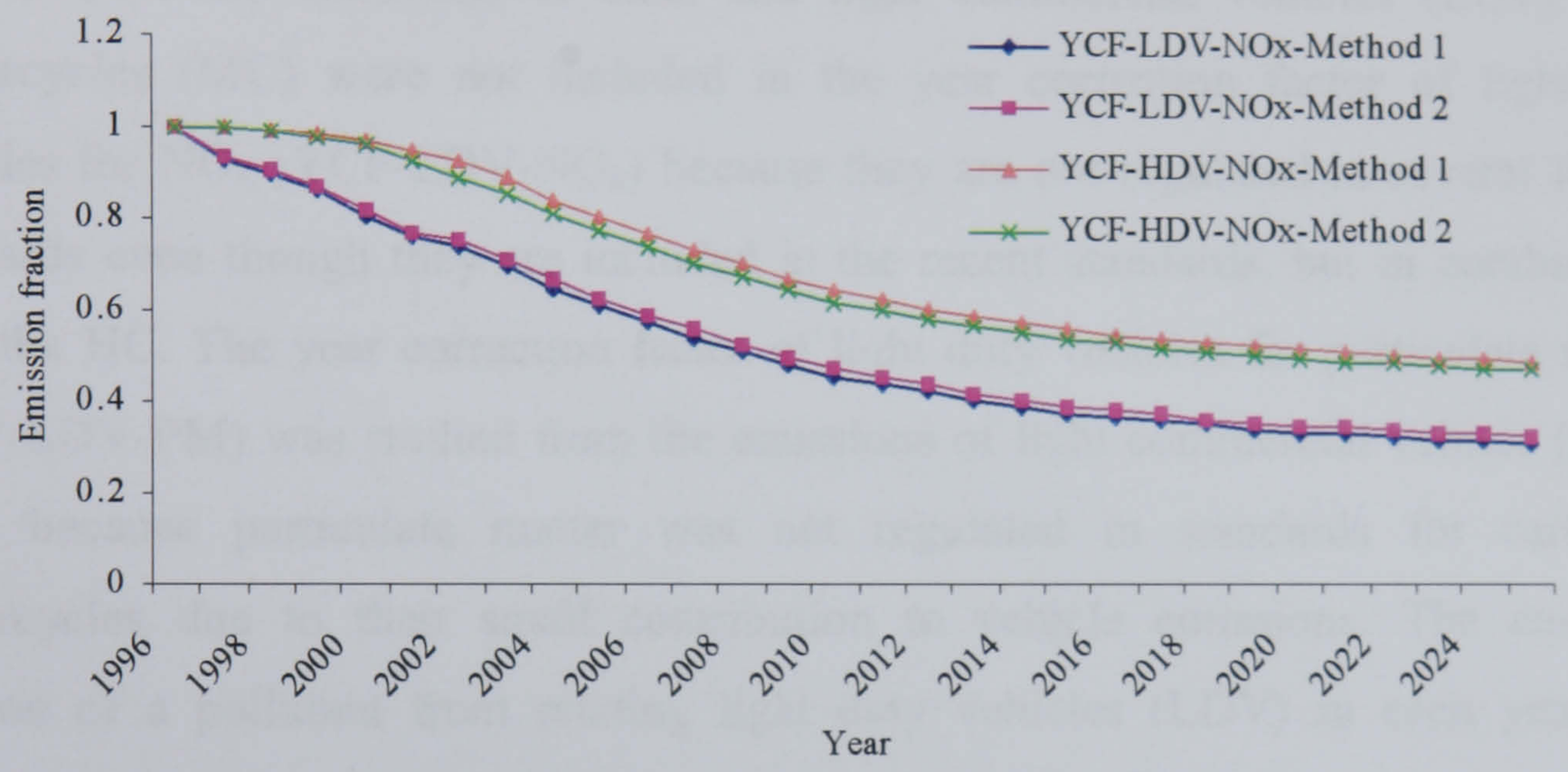


Figure 5.17 Predictions of DMRB and EU methods

The results show that the value and trend of the year correction factors for light duty vehicles (YCF-LDV) from both methods are very similar to each other. However, Figure 5.17 shows that the YCF-HDV-NO_x-Method 1 is a little higher than the YCF-HDV-NO_x-Method 2. This might occur from the separation of emission factors of Bus and Truck in the DMRB method. The emission rates are different, while in the Method 2, both Truck and Bus are regulated with the same emission rate in relevant standards. It can be seen that the Method 2 would be a surrogate method. However, both methods have some limits on their estimates because of the following.

1. The DMRB coefficients are limited to the Directives implemented in the UK. In this study, the coefficients from the Directive 83/351/EEC were used instead of those from the Directive 88/76/EEC. This replace might bring an error into the estimate.
2. In Method 2, most of the older Directives merged the emissions of NO_x and HC. Then, the estimation of NO_x's year correction factor was obtained from the combination of NO_x and HC and the fraction of NO_x were unknown. These might cause an error if the combined fraction were greatly different from one Directive to

the other. Even though NO_x and HC are separated in the new Directives, they were combined so as to fit with the older directives.

5.8.4 DMRB's year correction factor and Bangkok's year correction factor

The year correction factor for light duty vehicle (YCF-LDV) of CO and HC was studied from the emissions of car, light commercial vehicle (LCV), and motorcycle (MC). The year correction factor of light duty vehicles for NO_x (YCF-LDV-NO_x) was studied from the emissions of cars, and light commercial vehicles (LCV) only. Motorcycles (MC) were not included in the year correction factor of light duty vehicles for NO_x (YCF-LDV-NO_x) because they are not regulated in several former standards even though they are included in the recent standards, but in combination with the HC. The year correction factor of light duty vehicles for particulate matter (YCF-LDV-PM) was studied from the emissions of light commercial vehicle (LCV) only, because particulate matter was not regulated in standards for cars and motorcycles due to their small contribution to vehicle emissions. The emission fraction of a pollutant from relating light duty vehicles (LDV) in each year was summed and expressed as a proportion of emissions in 1996.

The year correction factors of heavy duty vehicle for NO_x, CO, HC, and PM was estimated from the Truck and Bus category. This followed the same procedure as the year correction factor of light duty vehicles (YCF-LDV), but the heavy duty vehicle (HDV) emission fraction in the DMRB method was expressed relative to light duty vehicle (LDV) emissions in 1996 (Highways Agency, 1999), instead of its 1996 fraction. The emission fraction of light duty vehicles (LDV) in Bangkok found in this research is depicted in Table 5.30. The year correction factor of light duty vehicles (YCF-LDV) and year correction factors of heavy duty vehicles (YCF-HDV) derived for Bangkok conditions under Method 2 were then compared to the DMRB's YCF applied in the GRAM model.

Table 5.30 LDV emission in Bangkok in 1996 (unit: g/km)

Pollutant	Car	LCV	MC	Total
NO_x	5.293	2.472	-	7.765
CO	18.843	8.287	26.637	53.767
HC	5.293	2.427	10.769	18.489
PM	-	0.262	-	0.262

Note: LCV = light commercial vehicle, MC = motorcycle

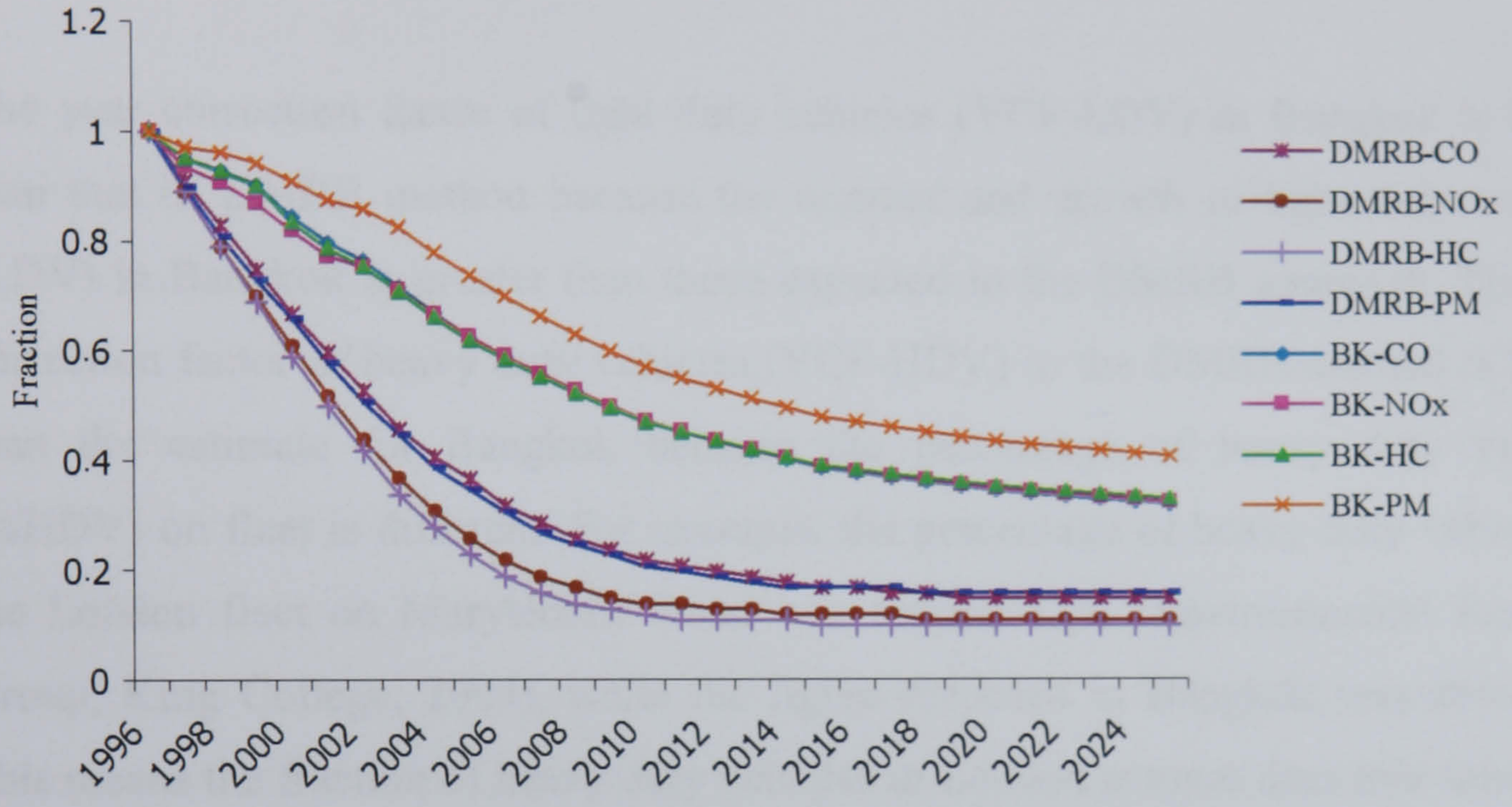


Figure 5.18 YCF-LDV of DMRB and Bangkok

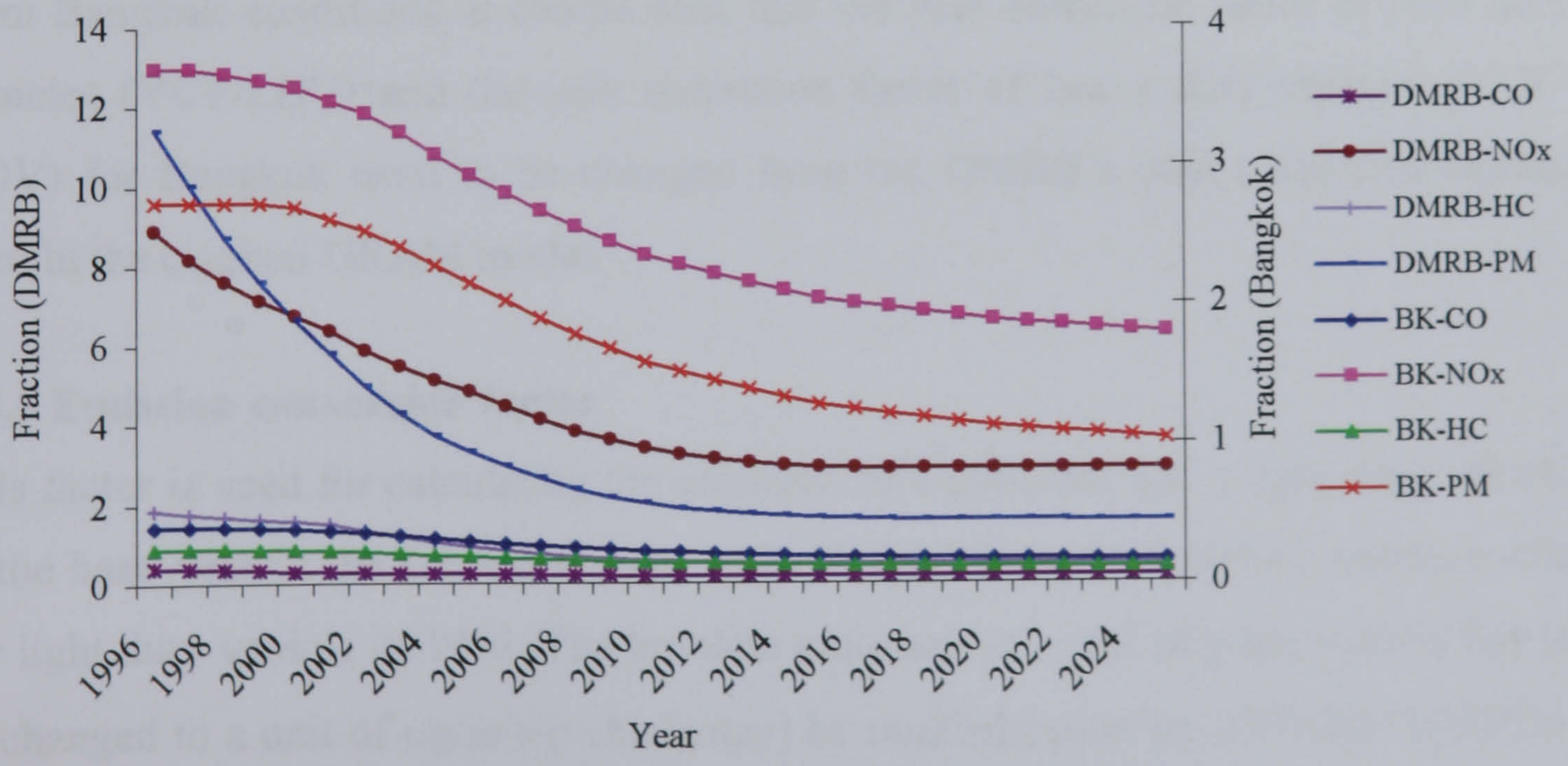


Figure 5.19 YCF-HDV of DMRB and Bangkok

Figures 5.18 and 5.19 indicate that the year correction factor of light duty vehicles (YCF-LDV) and the year correction factor of heavy duty vehicles (YCF-HDV) of DMRB and Bangkok were different. The results suggest that, in general, the reduction rate of emissions in Bangkok was not as fast as that estimated in the DMRB approach. This seems due to the later application of the EU emission limits, the larger growth rate of vehicles in Bangkok and a part from the overestimate of vehicle numbers after 2002.

The year correction factor of light duty vehicles (YCF-LDV) in Bangkok is higher than that of DMRB method because the number and growth of light duty vehicles (LDV) in Bangkok is greater than those expected in the DMRB approach. The year correction factor of heavy duty vehicles (YCF-HDV) in the DMRB method is higher than the estimate for Bangkok because the percentage of heavy duty vehicles (%HDV) on fleet is different. For example, the percentage of heavy duty vehicles in the London fleet on Marylebone Road was around 12% (Environmental Research Group, King College, 2004), while the figure recorded in Bangkok was about 3%. This means the fraction of heavy duty vehicles in London is more than four times that in Bangkok. Figure 5.19 also reflects a similar trend. The year correction factor of heavy duty vehicles (YCF-HDV) of particulate matter in 1996 was estimated as 11.44 and 2.75 for the DMRB method and Bangkok respectively. From the differences of the year correction factor found between DMRB method and the model developed from Bangkok conditions, it can be seen that the year correction factor of light duty vehicles (YCF-LDV) and the year correction factor of heavy duty vehicles (YCF-HDV) for Bangkok need to be changed from the DMRB's year correction factors used in the original GRAM model.

5.8.5 Emission conversion factor

This factor is used for calculating the emission of a pollutant for a light duty vehicle in the base year in the GRAM model. It is obtained from the baseline emission rate per light duty vehicle in 1996. The baseline emission in a unit of g/km/vehicle has to be changed to a unit of μg/m/s/(vehicle/day) by multiplication by $10^6/1000*3600*24$. The baseline emission rate per light duty vehicle in the DMRB method is for a travelling speed at 100 km/h. The baseline emission calculated from the EU Directives is based on a pattern of speed cycle, which is not exactly at 100 km/h. The

EU Emission test for the light duty vehicle is based on the ECE 15 and Extra Urban Driving Cycle (EUDC) (Sanger et al, 1997). With the introduction of the "Consolidated Emissions Directive" in July 1992 (DEH, 2004), the implementation became mandatory for all EU Member States. The EU "Consolidated Emissions Directive" required the combination of the ECE 15 and Extra Urban Driving Cycle (EUDC) test cycles to be used for emission measurements undertaken by the "Constant Volume Sampling" (CVS) technique. The ECE 15 mode driving cycle defines an urban test cycle to be used for emission measurements. The ECE 15 cycle is a very low duty cycle with a maximum speed of 50 km/h and an average speed of 19 km/h. It was thus not representative of many modes of driving. An additional Extra Urban Driving Cycle (EUDC) was agreed with a maximum speed of 120 km/h and 62.9 km/h in average. The Extra Urban Driving Cycle (EUDC) test is carried out after the standard ECE 15 test. Hence it can be seen that there are a number of vehicle speeds involved in the EU Emission test method for the EU Directives. It is unreliable to estimate the average speed of emission rates in Method 2. However, it was found in this research that the emission fractions estimated from the Methods 1 and 2 were very similar. Hence, it was assumed that the emissions of the Method 2 were based on the same average vehicle speed of 100 km/h. The 1996 emission rate per a light duty vehicle and its emission conversion factor in Bangkok was estimated accordingly.

The emission conversion factor used in the GRAM model was obtained from the emissions in London. This factor used in the original GRAM model and the new factor calculated from Bangkok conditions are shown in Table 5.31. It can be seen that the light duty vehicle emission rate of every pollutant in Bangkok is greater than those in London. Based on this research, this is due to the later implementation date of the same EU directive in Thailand, or at the same time, the older EU emission limits were implemented in Thailand. So, more pollutants are emitted from the light duty vehicles.

Table 5.31 LDV emission in London and Bangkok in 1996

Pollutant	London		Bangkok	
	Emission factor (g/km)[a]	Emission conversion factor (μg/m/s/(veh/day)	Emission factor (g/km)	Emission conversion factor (μg/m/s/(veh/day)
NOx	1.800	0.02083	2.588	0.02996
CO	4.980	0.05764	17.922	0.20743
HC	0.464	0.00537	6.163	0.07133
PM-PM_{10}	0.050	0.00058	0.087	0.00101

Source: [a] Highways Agency (1999)

5.9 Summary

Emission factors in Bangkok are different from those in London and from those used in the original GRAM model. The specific factors which need to be changed are the traffic condition, traffic growth rate, and percentage of 'Heavy Duty Vehicles', the meteorological factors; ambient temperature, wind speed and stagnant wind fraction, the NO_x/NO_2 relationship in both the empirical and theoretical approaches, the resuspended dust, the regional background PM_{10}, the year correction factor, the emission density, and the fraction of mobile source. It can be concluded that the original GRAM model needs some modification to allow for the different conditions between London and Bangkok.

Chapter 6

Development, Performance and Sensitivity of the Bangkok GRAM Model

6.1 Introduction

In the first part of this thesis, we have used a model developed and tested under UK conditions and specifically for the situations in London and applied this to Bangkok. The Bangkok situation is expected to be different from London in a number of ways and these are investigated and presented in Chapter 5. A new model was developed called the Bangkok GRAM model. The intention is to maintain the simple structure of the GRAM model, but allow differences between London and Bangkok to be investigated. This chapter describes the development, the performance, and the sensitivity of the Bangkok GRAM model.

6.2 Development of the Bangkok GRAM model

In the development of the Bangkok GRAM model, the winds, the relationship between NO_x and NO_2, the urban background concentration, and the year correction factors have been changed. The emission factors of the resuspended dust have been included in the prediction of the road contributions.

6.2.1 Treatment of wind flow Low wind speeds affect dispersion, especially very light winds often neglected in dispersion models. The GRAM model uses a wind speed of 3 m/s as an internal parameter for estimating the annual mean concentrations. The results from Chapter 5 shows that the annual wind speed in Bangkok should be 2 m/s with the fraction of calms equal to 20%. The Bangkok GRAM model alters this parameter in the input factors, and the model also includes a fraction of stagnant winds in the input data set, so as to improve the prediction of dispersion at low wind speed.

6.2.2 Relationship between NO_x and NO_2

Two options for estimating NO_2 concentrations are available in the GRAM model. Due to the different conditions found in the last chapter, the empirical approach (NO_2

Option 1) in the GRAM model, based on Derwant-Middleton curve in equation (1). was replaced by the relationships shown in the equation (2) or (3).

NO_2 = $7.2769 + 2736NO_x + (5.10366*10^{-4})NO_x^2 + (4.4561*10^{-7})NO_x^3$ ppb (1)

NO_2 = $14.222Ln(x) - 30.966$ ppb (2)

NO_2 = $227.092Ln(x) - 76.451$ $\mu g/m^3$ (3)

The NO_x/NO_2 relationship in the theoretical approach (NO_2 Option 2) depends on the NO_x level (NO_x), the photostationary constant (Z), and the levels of ozone and NO_2 (O_x) as shown in the following equations;

$NO_2 = 0.5(T - (T^2 - 4NO_xO_x)^{0.5})$ (1)

$T = NO_x + O_x + Z$ (1.1)

$O_x = 20 + aNO_x$ (1.2)

$Z = k_r/k_f$ (1.3)

Due to the fraction primary NO_2 from mobile source, 'a' in equation (1.2) in Bangkok is about 0.16, this fraction in sub-equations (1.2) in the NO_2 Option 2 is changed from the original internal value of 0.05 to an input factor of 0.16. The average photochemical reaction (Fisher, 2004a) over daylight hours under clear skies for London is $6.254x10^{-3}$ s^{-1}. For Bangkok's latitude, it is $6.849x10^{-3}$ s^{-1} under clear skies averaged over all day light hours. The default value of the backward rate constant (k_r) for London is $4x10^{-3}$ s^{-1}. To convert to Bangkok is difficult as the relationship represent typical conditions, which are not well defined. To start with, the value of $6x10^{-3}$ s^{-1} is tried for Bangkok. The forward rate constant (k_f) depends on the ambient temperature as shown in the following equations:

$k_f = 0.0517*\exp(-1450/(temp+273))$

where 'temp' means an ambient temperature in unit of degree Celsius (°C).

The GRAM model sets this internal parameter at 15°C. For the Bangkok GRAM model, k_r and k_f are the input parameters and 30°C is used for Bangkok's temperature.

6.2.3 Year correction factor

Bangkok mobile emission factors, as a function of year, were applied to the Bangkok GRAM model. The emission change in the new emission factor was lower than the DMRB factor, due to higher traffic growth rate, differences in the EU limit values in vehicle fleet and the implemented dates. This factor is kept as an internal parameter in the new model. The model also allows for the fraction change in non-mobile emissions in urban areas between the year of interest and the base year.

6.2.4 Urban background concentration

Another substantial improvement in the Bangkok GRAM model is in the context of improving urban background predictions with the principle of calculating differences in urban background concentration of pollutants between a central, an inner, and an outer zone. This improvement brings in the requirement for more input data: zone diameters, the emission density in zones, and the position of receptors from urban centre.

As defaults, distances of one third and one tenth of the urban diameter are defined as the diameters of the inner and central zones respectively from the urban centre. The typical emission density values of the inner and central zones are twice and three fold, respectively, those of the outer zone. The factors for the emission density in a zone, and the zone where the receptor is located, are calculated as a term called the 'distance correction factor'. This factor is then applied to the formulae for the 'urban background concentration'. This concept also used in the later version of the GRAM model called the 'GRAM Urban model' (Fisher, 2000a).

6.2.5 Resuspension of PM_{10}

Resuspended particle is a non-exhaust pollutant in origin. This factor has also been considered because of the great underestimation in the GRAM model of the PM_{10} in Bangkok. The study in Chapter 5 reveals that the resuspended dust, or non-exhaust particles, account for 20-25% of the road contribution of PM_{10} in Bangkok. Hence the Bangkok GRAM model has included factors describing the resuspended particles in the emission factors of light duty vehicles and heavy duty vehicles. Although the study was unable to quantify directly the results as the emission factors of the light duty vehicles and heavy duty vehicles, they were recently estimated by Abu-Allaban

et al (2003), the TRL Environment Group (2004), and the Air Quality Expert Group (AQEG) (2004a).

Abu-Allaban and his co-workers conducted measurements at roadside sites in Nevada and North Carolina, USA. They derived the emission factors of tailpipe, resuspended dust, and brake-wear from in-use vehicles. The non-exhaust particle factors were also derived from experiments conducted in the Hatfield Tunnel, Hertfordshire by Atmospheric Science Research Group (ASRG), University of Hertfordshire on behalf of the TRL Environment Group. The resuspended particle factor related to vehicular activity in the AQEG report was estimated from the analysis of particles observed at Marylebone Road, London. The factors of resuspended particle from these three studies are summarized in Table 6.1. The factor from the Abu-Allaban study is highest for both the heavy duty vehicles (HDV) and the light duty vehicles (LDV) factors. The TRL factors are the lowest figures. As a first attempt, the factors from all studies were tested and the results were compared as shown in Table 6.2. It was found that the predictions from the TRL Environment Group's factors and Air Quality Expert Group (AQEG) give the better agreement with the observations in Bangkok than the factors from Abu-Allaban et al (2003). However the AQEG's factors are for coarse particles, not PM_{10}. The AQEG's factors for the high duty vehicles (HDV) and the light duty vehicles (LDV) are greater than those of the TRL's factors by about four and three fold respectively. Nevertheless, the AQEG's factors give slightly higher estimates than those of TRL's factors, because of the low HDV fraction (~0.03) in Bangkok. The difference in estimates will probably be greater when they are applied to a vehicle fleet containing high proportion of HDV vehicles. For further study in this research, the TRL's factors were chosen.

Table 6.1 Emission factors of resuspended particle

Source	Particle	HDV (g/km)	LDV (g/km)
Abu-Allaban et al	PM_{10}	2.40	0.20
TRL Environment Group	PM_{10}	0.09	0.01
Air Quality Expert Group	PM_{coarse}	0.40	0.03

Table 6.2 The Bangkok GRAM model predicts PM_{10} in Bangkok in 2003 with different emission factors of resuspeded particle

unit: $\mu g/m^3$

	Abu-Allaban factor	TRL factor	AQEG factor
Dindaeng roadside station			
Observed PM_{10}	88.6	88.6	88.6
Regional PM_{10}	37.0	37.0	37.0
Modelled urban background PM_{10}	22.2	22.2	22.2
Modelled roadside PM_{10}	55.2	16.8	21.2
Modelled total PM_{10}	114.4	76.0	80.4
Ladphrao roadside station			
Observed PM_{10}	61.1	61.1	61.1
Regional PM_{10}	37.0	37.0	37.0
Modelled urban background PM_{10}	14.5	14.5	14.5
Modelled roadside PM_{10}	38.6	11.4	14.5
Modelled total PM_{10}	90.1	62.9	66.0
Thonburi Electricity roadside station			
Observed PM_{10}	61.6	61.6	61.6
Regional PM_{10}	37.0	37.0	37.0
Modelled urban background PM_{10}	17.1	17.1	17.1
Modelled roadside PM_{10}	25.9	7.0	9.1
Modelled total PM_{10}	80.0	61.1	63.2

6.3 Performance of the GRAM model and the Bangkok GRAM model

6.3.1 Methodology

The GRAM and the Bangkok GRAM models are then tested against measurements in Bangkok using the measurements at three roadside and three urban background air quality monitoring stations. The 2003 measurements conducted by Pollution Control Department and the traffic data surveyed by Traffic and Transportation Department, Bangkok Metropolitan Administration were employed. This agency surveys traffic conditions at major junctions during 07.00-19.00 hour, and the Motorcycle category is not included in the survey (Traffic and Transport Department, BMA, 2004). The traffic volume from this agency was extrapolated to cover 24 hours, and included the 'motorcycle' component. Regarding the diurnal variation of traffic volume surveyed by the office of the Commission for the Management of Land Traffic in 1997-1998 (OCMLT, 1998, 1999), the traffic volume during 20.00-06.00 hour was around one third of the day-time volume. Based on the OCMLT survey, it was assumed that there was one third of flow during 07.00-19.00 hour for traffic flow during 20.00-06.00 hour. The composition of registered motorcycles in Bangkok is about 40%. To include the motorcycle in to traffic flow surveys, the factors of 1.3 and 1.1 were

multiplied to daytime surveys and night time surveys respectively. The input data is shown in Table 6.3.

Table 6.3 Input data for testing the performance of the Bangkok GRAM model

Factor	Dindaeng	Ladphrao	Thonburi Electricty	Nonsi	Klong Jun	Singharach
Vehicle speed (km/h)	17	20	35	-	-	-
Vehicle flow (vehicle/day)	120000	85000	65000	-	-	-
Year number	2003	2003	2003	2003	2003	2003
Traffic growth (%/y)	9	9	9	9	9	9
Fraction HGV	0.03	0.03	0.03	0.03	0.03	0.03
Diameter urban area (km)	40	40	40	40	40	40
Diameter inner zone (km)	13	13	13	13	13	13
Diameter central zone (km)	4	4	4	4	4	4
Base year for emissions inventory	2002	2002	2002	2002	2002	2002
NO_x emission density in outer zone ($kt/km^2/y$)	0.04	0.04	0.04	0.04	0.04	0.04
NO_x emission density in inner zone ($kt/km^2/y$)	0.08	0.08	0.08	0.08	0.08	0.08
NO_x emission density in central zone ($kt/km^2/y$)	0.12	0.12	0.12	0.12	0.12	0.12
PM_{10} emission density in outer zone ($t/km^2/y$)	6	6	6	6	6	6
PM_{10} emission density in inner zone ($t/km^2/y$)	12	12	12	12	12	12
PM_{10} emission density in central zone ($t/km^2/y$)	18	18	18	18	18	18
Regional PM_{10} (mg/m^3)	37	37	37	37	37	37
Emission factor for the light duty vehicles (g/km)	0.01	0.01	0.01	-	-	-
Emission factor for the heavy duty vehicles (g/km)	0.09	0.09	0.09	-	-	-
Position of receptor from centre (km)	3.2	8.5	5.8	4	13	11.2
Fraction stagnant winds	0.2	0.2	0.2	0.2	0.2	0.2
Mean wind speed (m/s)	2	2	2	2	2	2
Background ozone (ppb)	20	20	20	20	20	20
Temperature (Celsius)	30	30	30	30	30	30
Fraction mobile sources	0.9	0.9	0.9	0.9	0.9	0.9
Reaction rate NO_2->NO 1/s	0.006	0.006	0.006	0.006	0.006	0.006
Fraction primary NO2 (ppb)	0.16	0.16	0.16	0.16	0.16	0.16
Low wind enhancement factor	0.76923	0.76923	0.76923	0.76923	0.76923	0.76923
Non-mobile source factor	1	1	1	1	1	1
Height of buildings(m)	0	0	0	0	0	0
Width of road (m)	25	15	15	-	-	-
Number of distances from road	1	1	1	1	1	1
Distance from road (m)	15	15	20	100	100	100

The root mean square difference (RMSD), the fractional bias (Fb), and the normalized mean square error (NMSE) were used to estimate model performance. The first factor has been used for model selection at the beginning of this thesis. The Fb and NMSE have also been used in previous studies (for example, Owen et al., 1999; Kukkonen, et al. 2001b; Mediavilla-Sahagun, and ApSimon, 2003). Calculations of these factors are defined as:

$$\text{RMSD} = \sqrt{(1/n)\,\Sigma\,(C_p - C_o)^2}$$

$$\text{Fb} = (\overline{C}_o - \overline{C}_p) / (0.5*(\overline{C}_o - \overline{C}_p))$$

$$\text{NMSE} = \overline{(C_o - C_p)^2} / (\overline{C}_o * \overline{C}_p)$$

where C_p is the predicted value, C_o is the observed value, and n is the number of value. $\overline{C}_p$ is the average predicted value, $\overline{C}_o$ is the average observed value.

The value of RMSD, Fb and NMSE in a perfect model would be 0. For the Fb, the negative value means an over-prediction, while the positive value means under-prediction. Thus a value of 0.1 means an average under-prediction of 10% (Mediavilla, and ApSimon, 2003). The assessment of model performance was carried out considering separately monitoring stations of the roadside and urban background types. Moreover the USEPA does not give a specific guidance on the quantification of model uncertainty (US.EPA, 2004), but suggests the use of the ''best estimate'', whilst, the accuracy requirements for air quality models given in the EU first Daughter Directive (Van den Hout, No date) are given as shown in Table 6.4.

Table 6.4 Overview of the accuracy requirements of the first Daughter Directive

	SO_2, NO_2, NO_x	Particulate matter and lead
Hourly averages	50% - 60%	-
Daily averages	50%	Not defined at present
Annual averages	30%	50%

Source: Van den Hout (No date)

6.3.2 Results and discussion

The statistical analysis as shown in Table 6.5 indicates that the Bangkok GRAM model gives better agreement with the 2003 measurements than the GRAM model in both NO_2 and PM_{10} at all locations. The poorer prediction of the GRAM model seems to occur from the larger emission improvement estimated by the DMRB's year correction factor than that of Bangkok GRAM model as discussed in Chapter 5. The uncertainty of the predictions in the Bangkok GRAM model is well within the requirements for air quality models given in the EU first Daughter Directive.

Table 6.5 Performance of the GRAM and Bangkok GRAM models

Factor	Roadside station			RMSD	Fb	NMSE
	Dindaeng	Ladphrao	Thonburi E.			
Observed NO_2 in 2003 (ppb)	44.5	32.7	27.7	-	-	-
Bangkok GRAM NO_2-Option 1 (ppb)	44.0	38.3	35.5	5.55	-0.12	0.02
Bangkok GRAM NO_2-Option 2 (ppb)	46.7	35.6	31.4	3.00	-0.08	0.01
GRAM NO_2 (ppb)	23.2	22.2	20.4	14.34	0.46	0.27
Observed PM_{10} in 2003 ($\mu g/m^3$)	88.6	61.1	61.6	-	-	-
Bangkok GRAM PM_{10} ($\mu g/m^3$)	76.0	62.9	61.1	7.35	0.05	0.01
GRAM PM_{10} ($\mu g/m^3$)	46.7	45.8	45.1	27.46	0.42	0.23
	Urban background station			RMSD	Fb	NMSE
	Nonsi	Klong Jun	Singharach			
Observed NO_2 in 2003 (ppb)	29.6	20.9	20.6	-	-	-
Bangkok GRAM NO_2-Option 1 (ppb)	28.2	22.0	22.1	1.34	-0.02	0.00
Bangkok GRAM NO_2-Option 2 (ppb)	22.7	17.0	17.1	5.00	0.22	0.06
GRAM NO_2 (ppb)	18.6	18.6	18.6	6.59	0.24	0.10
Observed PM_{10} in 2003 ($\mu g/m^3$)	59.1	52.5	56.1	-	-	-
Bangkok GRAM PM_{10} ($\mu g/m^3$)	57.6	50.3	50.4	3.63	0.06	0.00
GRAM PM_{10} ($\mu g/m^3$)	44.1	44.1	44.1	12.10	0.24	0.06

6.4 Model sensitivity

6.4.1 Methodology

Several of the internal parameters with fixed values in the GRAM model have been changed to be variable input factors in the Bangkok GRAM model. In all 17 data sets were involved in the sensitivity test of the Bangkok GRAM model for the prediction of NO_x and PM_{10} concentrations as shown in Table 6.6. The data from the Dindaeng roadside site was chosen as the base case. When one factor was varied, the others were kept constant. This gives the degree of significance of each factor on the prediction.

6.4.2 Results and discussion

Figures 6.1 and 6.2 illustrate the sensitivity of the Bangkok GRAM model for the prediction of NO_x and PM_{10} concentrations respectively. The sensitivity of the model is summarized in Table 6.7. The results show that the variation in each factor causes more or less impact on the model prediction. The predictions of the Bangkok GRAM model are not sensitive to the fraction of the traffic growth rate, and the fraction of mobile source. The wind speed is very sensitive on the predictions of NO_x and PM_{10}. The heavy duty vehicles (HDV) fraction is also very sensitive to the prediction of

NO_x. It should be noted that the HDV fraction influences the predictions of both the road contribution and the urban background contribution. Thus, the accuracy of the input data has to be a matter of concern, especially those showing high sensitivity to small degrees of variation.

6.5 Summary

We conclude that for assessing the future air quality in Bangkok, the new program is suitable. From the policy point of view, one is interested in the changes in concentration between now and future dates, especially 2010. Air quality objectives in London and Bangkok are different but we have a suitable tool for making policy decisions concerning urban air quality management in the two cities.

Table 6.6 Input data for testing Bangkok GRAM sensitivity

Factor	Constant	Variation
Vehicle speed (km/h)	17	10, 13, 15, 20, 25, 30, 50, 60, 70, 80, 90, 100, 120, 130,150
Vehicle flow (x1000 vehicle/day)	120	10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 130, 140, 150
Year number	2003	-
Traffic growth (%/y)	9	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15
Fraction HDV	0.03	0.01, 0.02, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 13
Diameter urban area (km)	40	-
Diameter inner zone (km)	13	-
Diameter central zone (km)	4	-
Base year for emissions inventory	2002	-
NO_x emission density in outer zone (kt/km^2/y)	0.04	0.01, 0.02, 0.03, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10
NO_x emission density in inner zone (kt/km^2/y)	0.08	0.02, 0.04, 0.06, 0.10, 0.12, 0.14, 16, 0.18, 0.20
NO_x emission density in central zone (kt/km^2/y)	0.12	0.03, 0.06, 0.09, 0.15, 0.18, 0.21, 0.24, 0.27, 0.30
PM_{10} emission density in outer zone (t/km^2/y)	6	1, 2, 3, 4, 5, 7, 8, 9, 10
PM_{10} emission density in inner zone (t/km^2/y)	12	2, 3, 6, 8,10, 14, 16, 18, 20, 22, 24
PM_{10} emission density in central zone (t/km^2/y)	18	3, 6, 9, 12, 15, 21, 24, 27, 30, 33, 36
LDV resuspeded dust factor (g/km)	0.01	0.0, 0.03, 0.05, 0.10, 0.15, 0.20
HDV resuspended dust factor (g/km)	0.09	0.0, 0.05, 0.5, 1.0, 1.5, 2.0
Regional PM_{10} ($\mu g/m^3$)	37	-
Position of receptor from centre (km)	3.2	1, 2, 4, 5, 6, 7, 8, 9, 10
Fraction stagnant winds	0.2	0, 0.4, 0.6, 0.8, 1.0
Mean wind speed (m/s)	2	0.5, 1, 3,4,5
Background ozone (ppb)	20	-
Temperature (Celsius)	30	-
Fraction mobile sources	0.9	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1.0
Reaction rate NO2->NO 1/s	0.006	-
Fraction primary NO2 (ppb)	0.16	-
Low wind enhancement factor	0.76923	-
Non-mobile source factor	1	-
Height of buildings (m)	0	-
Width of road (m)	25	-
Number of distances from road	1	-
Distance from road (m)	15	1, 2, 3, 4, 5, 10, 20, 30, 40, 50, 70, 100

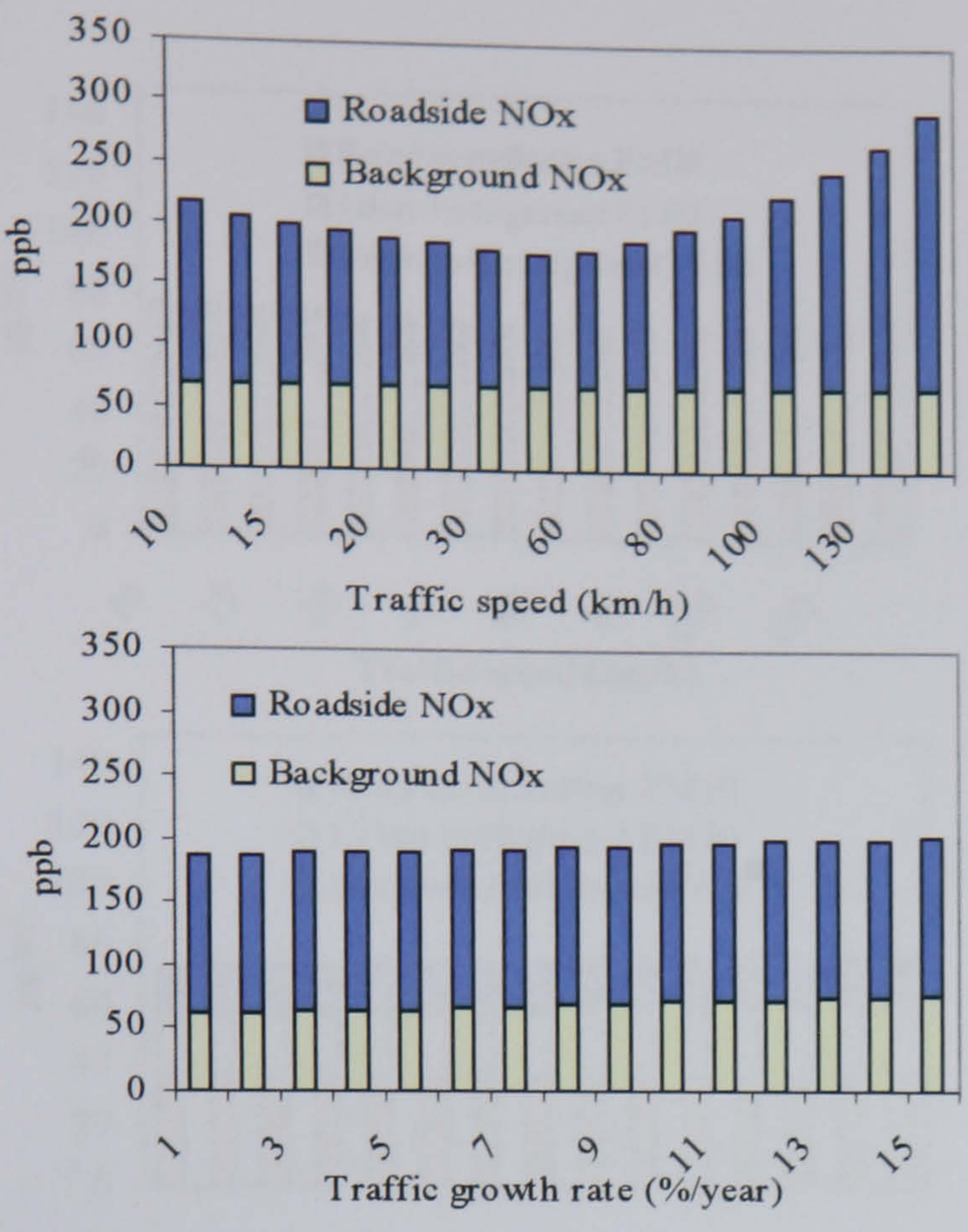
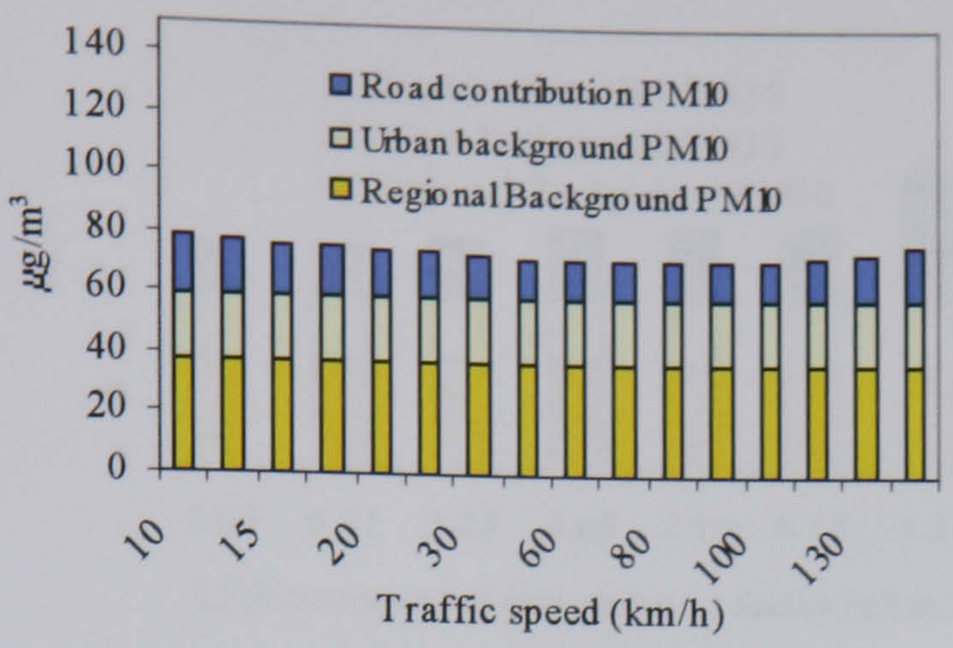
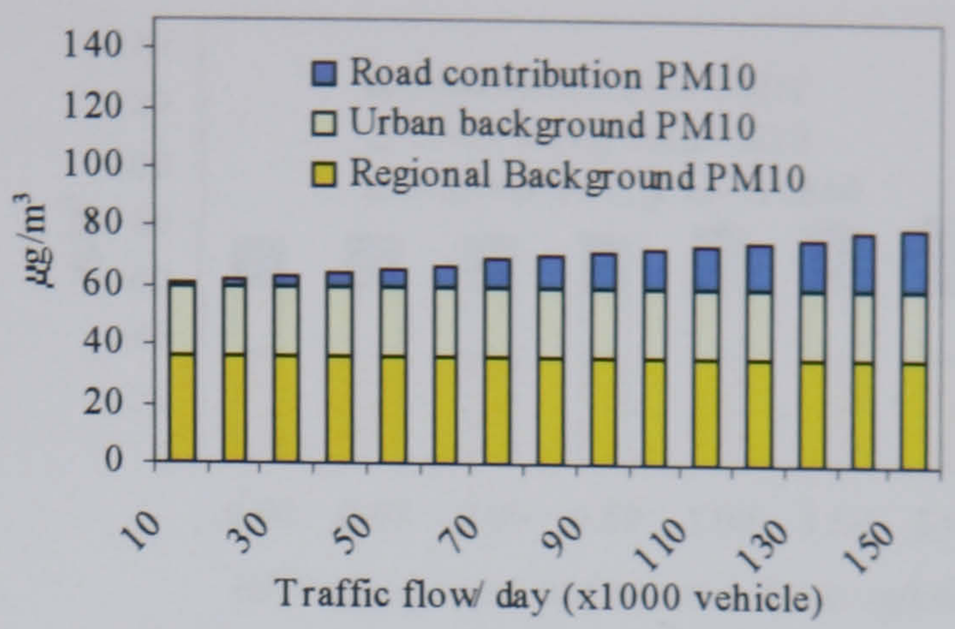
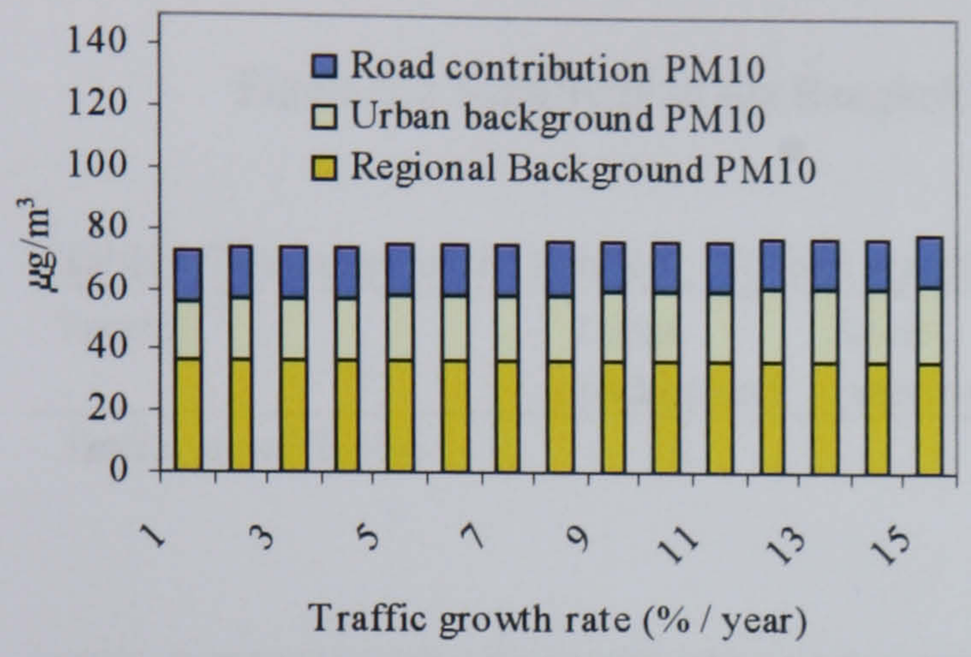
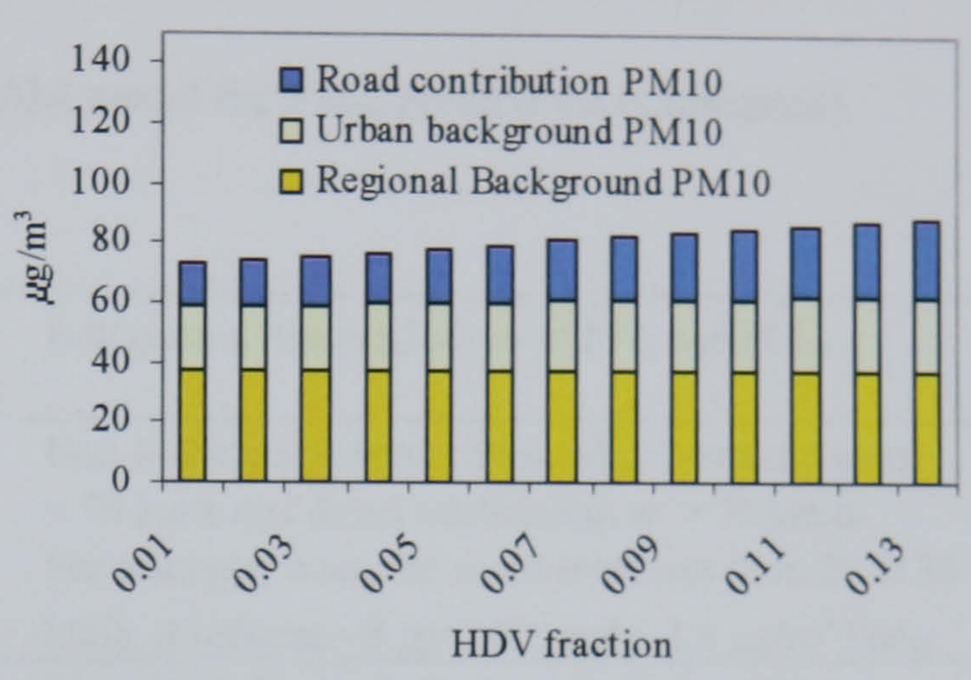


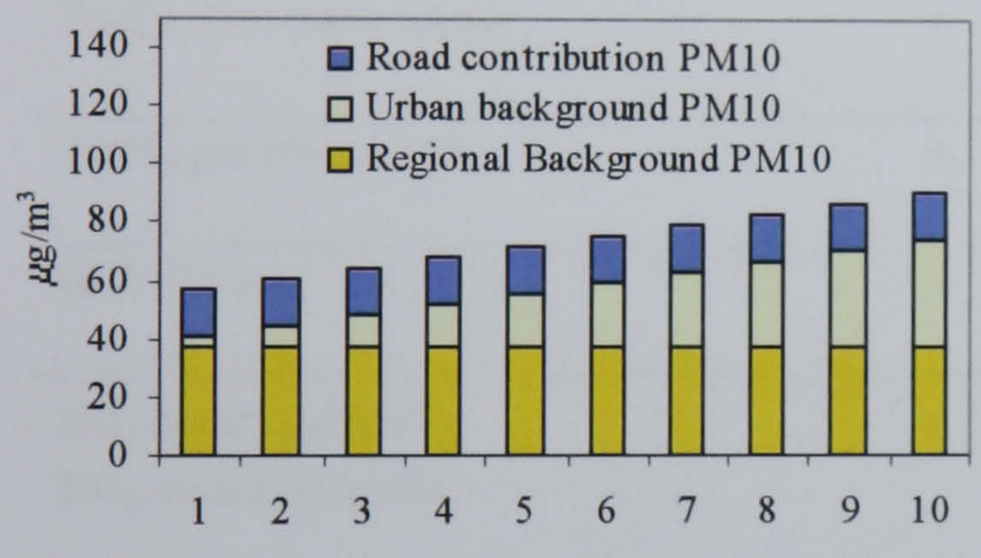
Figure 6.1 Sensitivity of the Bangkok GRAM model for NO_x prediction

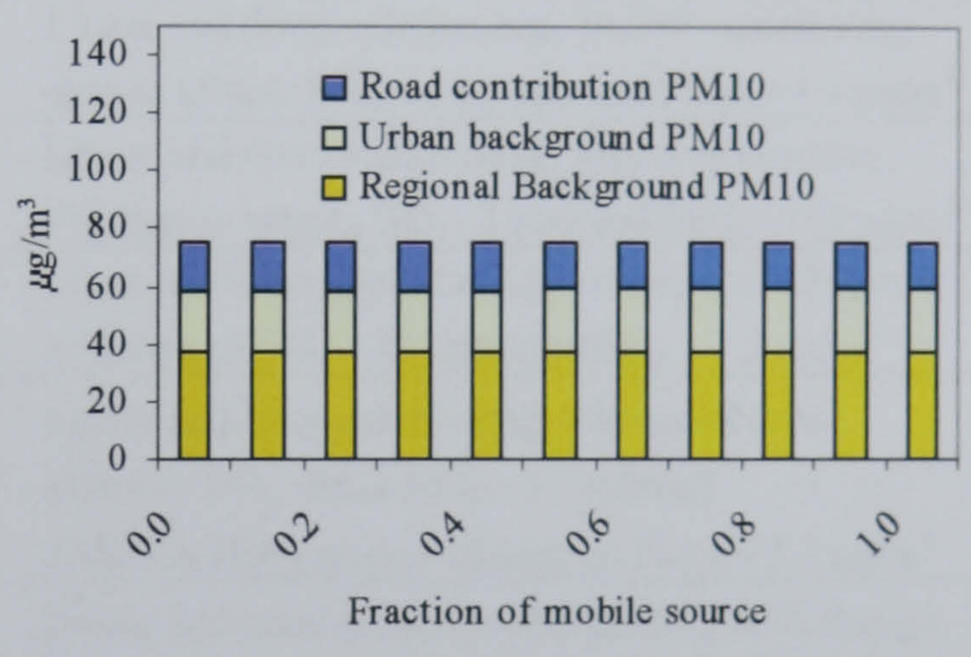


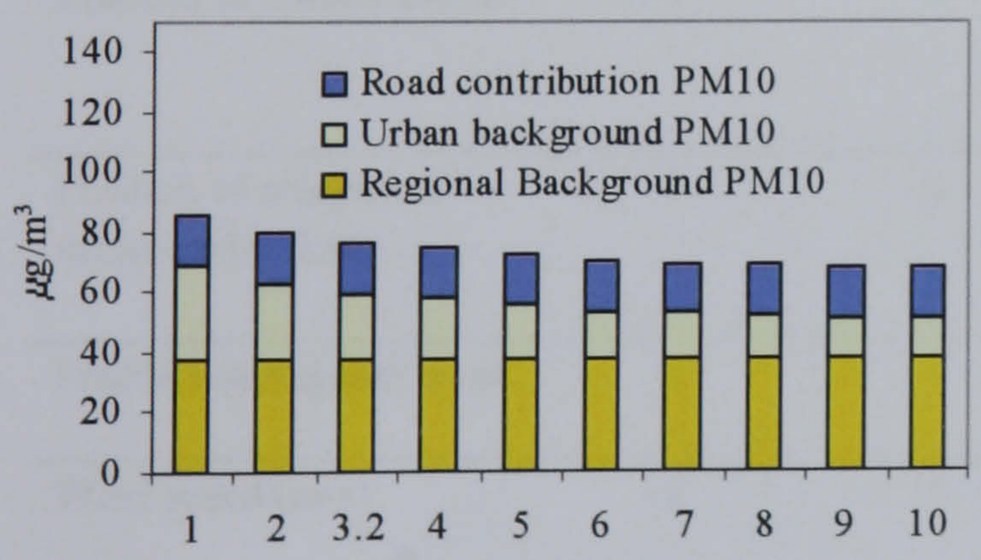


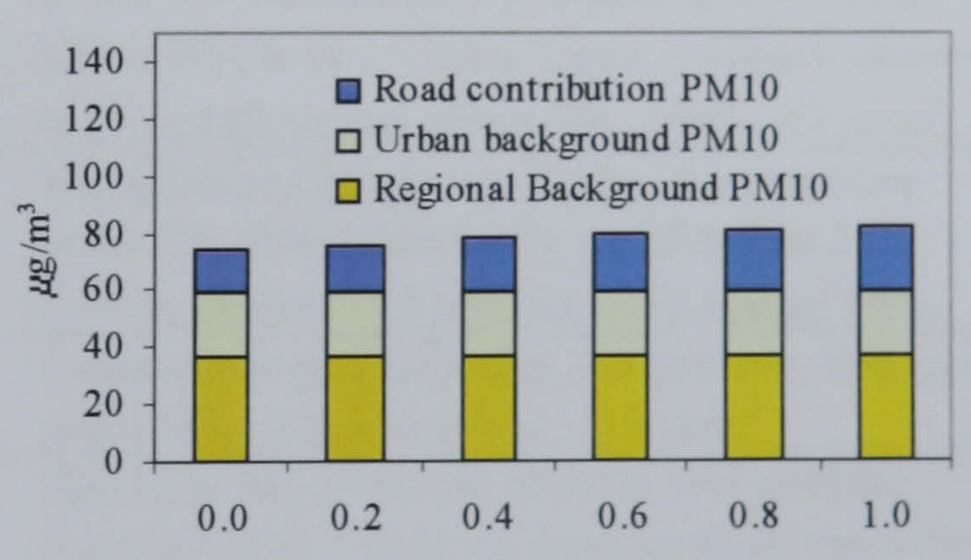


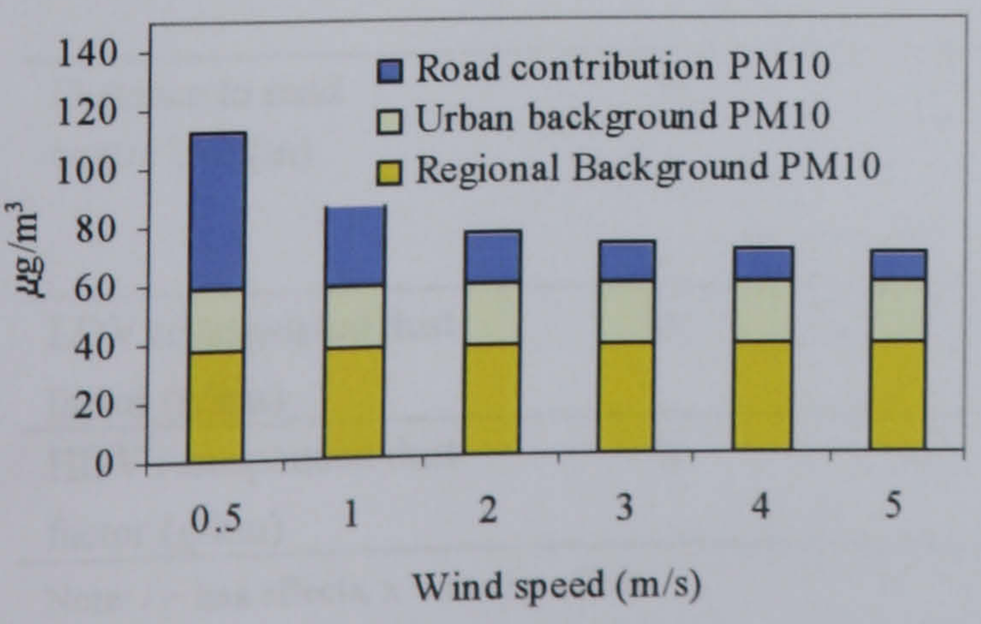












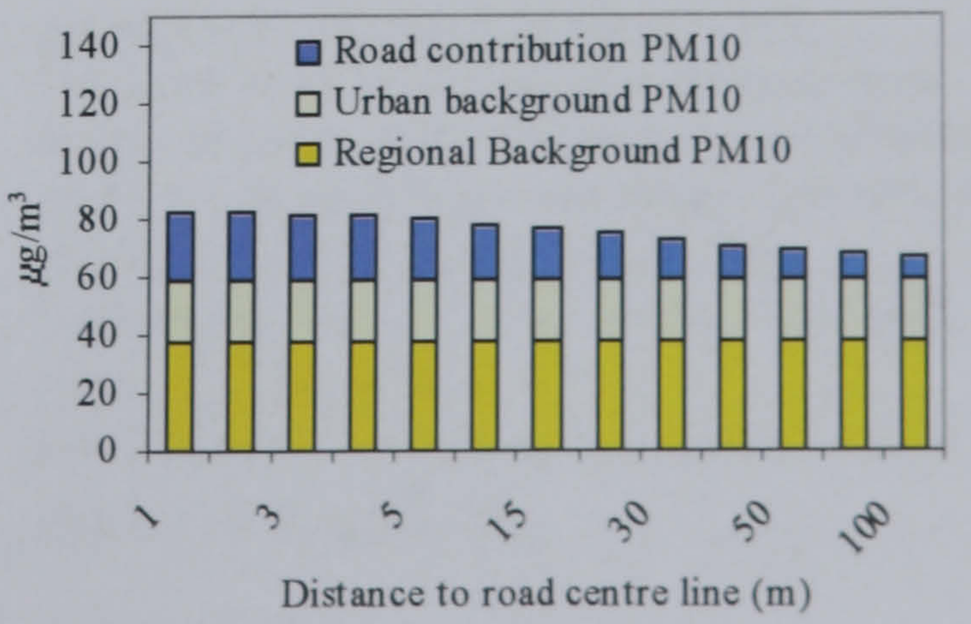
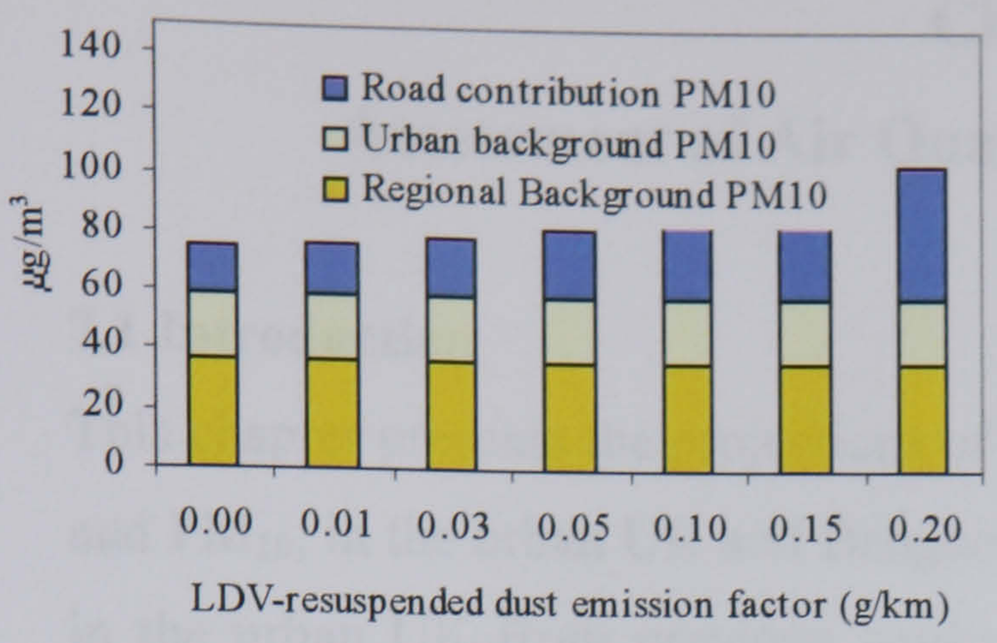


Figure 6.2 Sensitivity of the Bangkok GRAM model for PM_{10} predictions



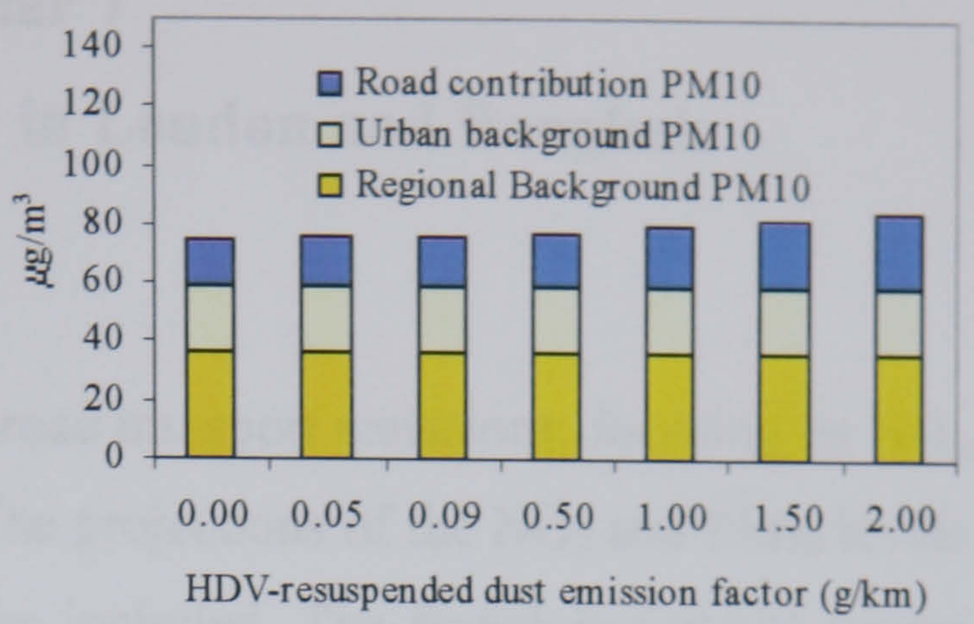


Figure 6.2 Sensitivity of the Bangkok GRAM model for PM_{10} predictions (Continued)

Table 6.7 Summary of the Bangkok GRAM's sensitivity

Factor	Urban background	Road contribution	Influence on the predictions of NO_x and PM_{10}
Traffic speed (km/h)	x	/	Non-linear and inverse relationship when the speed < 70 km/h and direct relationship at > 70 km/h. For example, when the speed increases from 20 to 30 km/h, it reduces ~ 8 ppb NO_x and ~ 1.4 µg/m^3 PM_{10}
Traffic flow (vehicle/day)	x	/	Linear and direct relationship, 10,000 vehicles/day change affects NO_x ~ 10.5 ppb and PM_{10} ~ 1.4 µg/m^3
Traffic growth rate (%)	/	x	Linear and direct relationship, very low sensitive, 1% change affects NO_x ~1 ppb and PM_{10} ~ 0.3 µg/m^3.
HDV fraction	/	/	Linear and direct relationship, variation of 1% gives a change of NO_x ~ 15 ppb and PM_{10} ~ 1.3 µg/m^3
NO_x density (kt/km^2/y) PM_{10} density (t/km^2/y)	/	x	Linear and direct relationship, change of 0.01 kt/km^2/y NO_x varies NO_x ~ 17 ppb and 1 t/km^2/y PM_{10} gives a change on PM_{10} ~ 3.7 µg/m^3
Fraction of mobile source	/	x	Linear and inverse relationship in NO_x, 10% change affects NO_x level ~ 0.5 ppb. Linear and direct relationship in PM_{10}, 10% change affects PM_{10} level ~ 0.1 µg/m^3.
Position of receptor to urban centre (km)	/	x	Non-linear and inverse relationship, more sensitive under 5 km from urban centre, e.g. alter from 5 km to 4 km changes ~ 7.5 ppb NO_x and 2.4 µg/m^3 PM_{10}
Fraction of stagnant wind	x	/	Linear and direct relationship, low sensitive, 10% change varies NO_x ~ 6 ppb and PM_{10} ~ 0.8 µg/m^3
Wind speed (m/s)	x	/	Non-linear and inverse relationship, very sensitive when the winds < 3m/s, e.g.when the winds reduce from 3 to 2 m/s, NO_x increases ~ 30 ppb, PM_{10} ~ 4 µg/m^3 and even more sensitive if the winds <2 m/s
Distance to road centre line (m)	x	/	Non-linear and inverse relationship, distances closer to the road centre line is more sensitive than the further away. For instance, the distance changes from 20 to 30 m, it reduces ~18 ppb NO_x and ~2 µg/m^3 PM_{10}
LDV resuspended dust factor (g/km)	x	/	Linear and direct relationship, variation of 0.01 g/km changes ~ 1.5 µg/m^3 PM_{10}.
HDV resuspended dust factor (g/km)	x	/	Linear and direct relationship, variation of 0.01 g/km changes ~ 0.05 µg/m^3 PM_{10}.

Note: / = has effects, x = has no effect

Chapter 7

Assessment of Air Quality in London and Bangkok

7.1 Introduction

This chapter presents the projections of the road transport emissions, focusing on NO_x and PM_{10}, in the urban UK and Bangkok. The projections of the NO_2 and PM_{10} levels in the urban UK from previous works were included. The Bangkok GRAM model was used as a tool to estimate the projections of NO_2 and PM_{10} concentrations in Bangkok during 2003-2025. The needs of additional measures on road transport emissions in the UK and Thailand were mentioned and the scenarios of strategies as the additional measures for improving air quality in Bangkok were proposed and assessed.

7.2 Projections of the road transport emissions in London and Bangkok

Projections of UK emissions are compiled by the National Atmospheric Emission Inventory (NAEI) (AQEG, 2004b). The base emission projections are currently from a 2001 base year and are calculated from a combination of road traffic activity projections and knowledge of the expected emission characteristics of the vehicle fleet in the future. Trends and projections of road transport emissions in the UK between 1970 and 2025 are shown in Figure 7.1. The figure illustrates that the emissions of NO_x and PM_{10} are going down in the future years. This due to the penetration of newer vehicles meeting more stringent emission limit value (AQEG, 2004b). However, total emissions may start to rise if vehicle number increases.

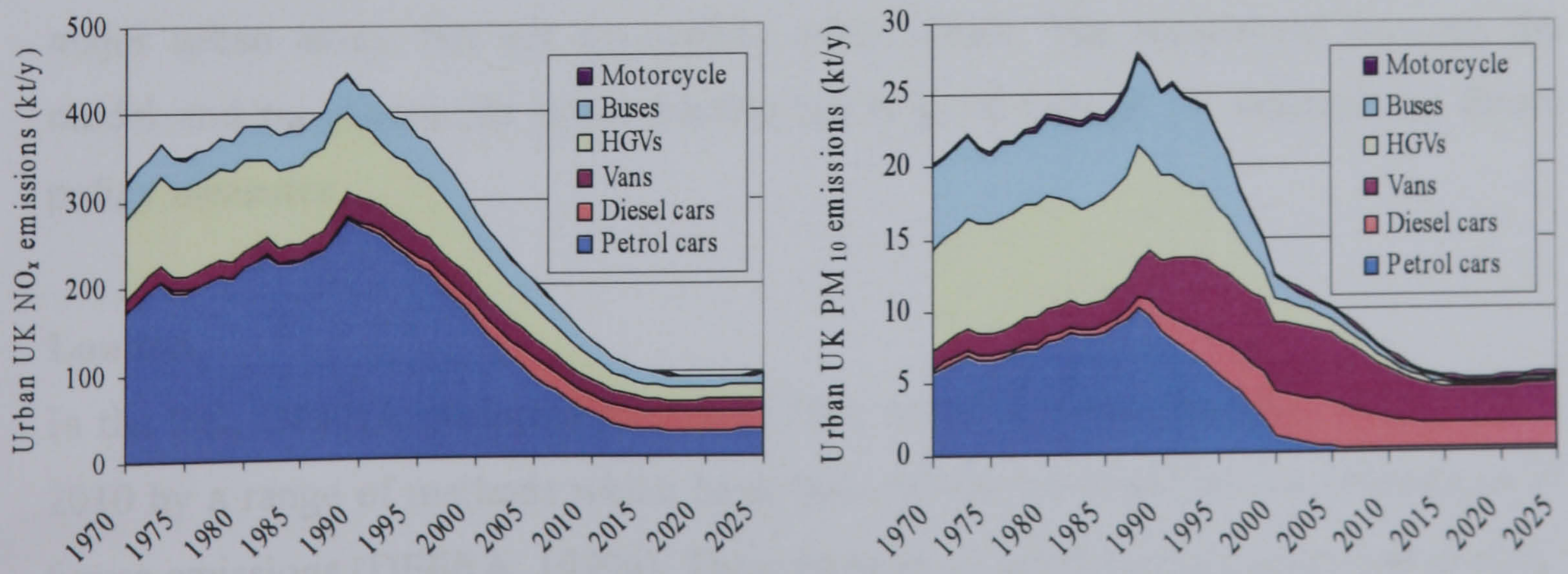


Figure 7.1 Trend and projections of road transport emissions of NO_x and PM_{10} in UK urban area

Source: AQEG (2004a, 2004b)

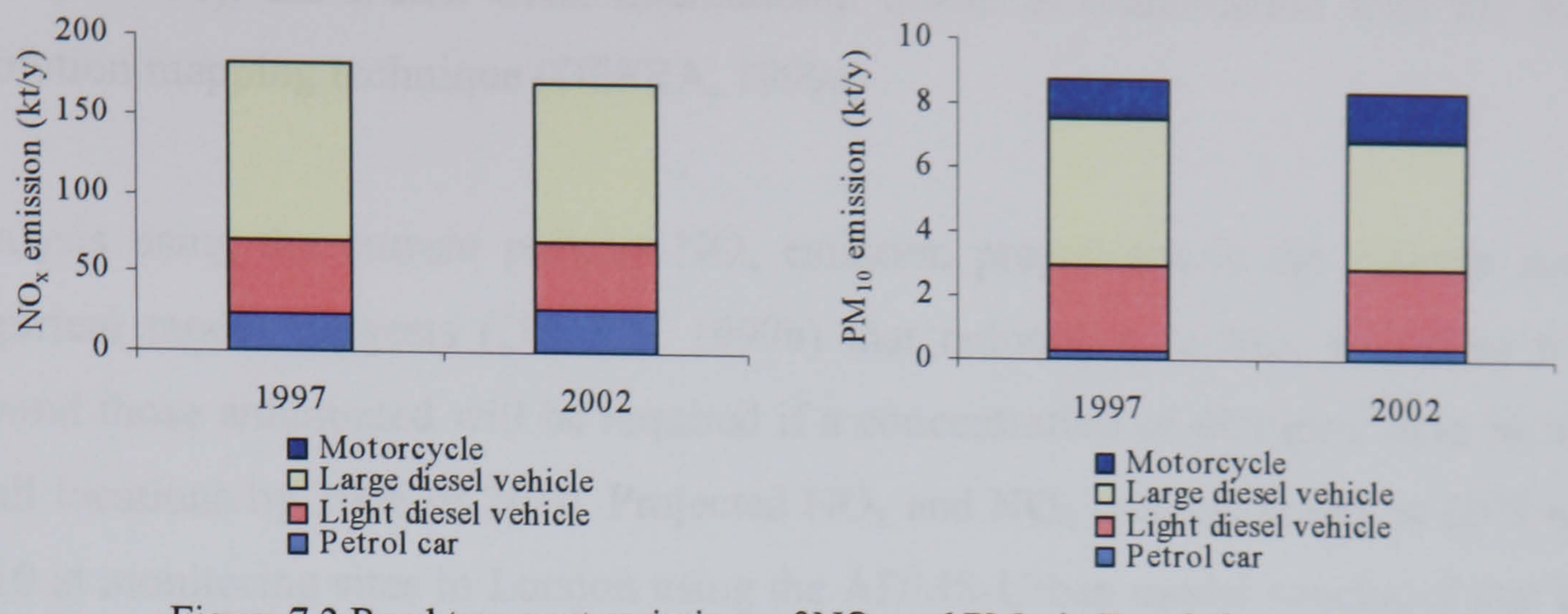


Figure 7.2 Road transport emissions of NO_x and PM_{10} in Bangkok

Similar trends arise under the current policy on emission reduction in Bangkok as seen in Figure 7.2 (see Appendix 2). The figure indicates that road transport emissions of NO_x and PM_{10} in Bangkok were expected to decrease but very slightly during the period of five years between 1997 and 2002, unlike a sharp decline estimated in the UK in the same period. Even though newer vehicles meeting more stringent emission limit values penetrate into the vehicle fleet in Bangkok, the decline was offset by the high growth rate of around 9% a year. Hence, one can expect some extra measures to be added to the current emission policy in order to increase the rate of traffic emission reduction in Bangkok.

7.3 Projections of the NO_2 and PM_{10} concentrations in London and Bangkok

It is not sufficient to consider just national total emissions. Limit values are set in term of concentrations. Highest concentrations in the UK occur in central London and similarly Thailand in Bangkok. Hence one requires one more detailed assessment of major urban areas, but not necessarily every detail. The assessment between the model and measurements is not perfect but is good enough for determining future policy measures.

London

In the UK, DEFRA projected the future NO_2 and PM_{10} concentrations during 2002-2010 by a range of methods which have been developed based on the estimations of future emissions (DEFRA, 1999a). These have involved the simple empirical models: the empirical site-specific projection models and a simpler 'year factor' approach to more sophisticated deterministic models, e.g. the ADMS-Urban model (DEFRA,

1999a, 1999b), the Dutch CAR International model in combination with the high resolution mapping technique (DEFRA, 1999a).

Analysis using the current policies NO_x emission projections in the national scale empirical model suggests (DEFRA, 1999b) that reductions in NO_x emissions well beyond those anticipated will be required if a concentration of 40 $\mu g/m^3$ is to be met at all locations by 2005 or 2010. Projected NO_x and NO_2 concentrations in 2005 and 2010 at monitoring sites in London using the ADMS-Urban model concluded that the total number of sites with modelled annual mean NO_2 levels greater than its objective still exist, but reduce in 2010. Outside London the exceedences are likely to be confined to the roadsides of busy roads while many roadside locations and some background locations are expected to exceed in London. Similar conclusions are shown in the PM_{10} projections. PM_{10} projections showed that it is unlikely that target levels will be achieved on current policies at the some urban background and kerbside locations and to achieve 2010 objective, PM_{10} levels would need to decline at rates significantly higher than their historic rates at urban background sites and this does not appear plausible (DEFRA, 1999b).

Bangkok

The projected NO_2 and PM_{10} levels at roadside and urban background locations during 2003-2025 modelled by the Bangkok GRAM model are shown in Figures 7.3 and 7.4. The predictions were based on the 2003 base-year data as shown in Table 6.3. The projections of NO_2 were taken from the Option 1 (the empirical approach).

The model predicts that under the current policy the concentrations of NO_2 and PM_{10} in many locations of roadside and urban background sites in Bangkok, in the future years, will keep exceeding its guideline or standard. The levels of NO_2 and PM_{10} at roadside sites were estimated to slightly decrease before 2010, and to increase later. It could be explained that the technology-based emission reduction was offset by the vehicle growth in Bangkok. Because of the growth of traffic, the model predicted the continual increase of NO_2 and PM_{10} levels at urban background areas since the base year. To improve air quality, some additional measures on emission reduction are needed to include into the current policy measures. Otherwise, in the future years.

even air quality at urban background sites (e.g. Nonsi station) will be as poor as some roadside sites are.

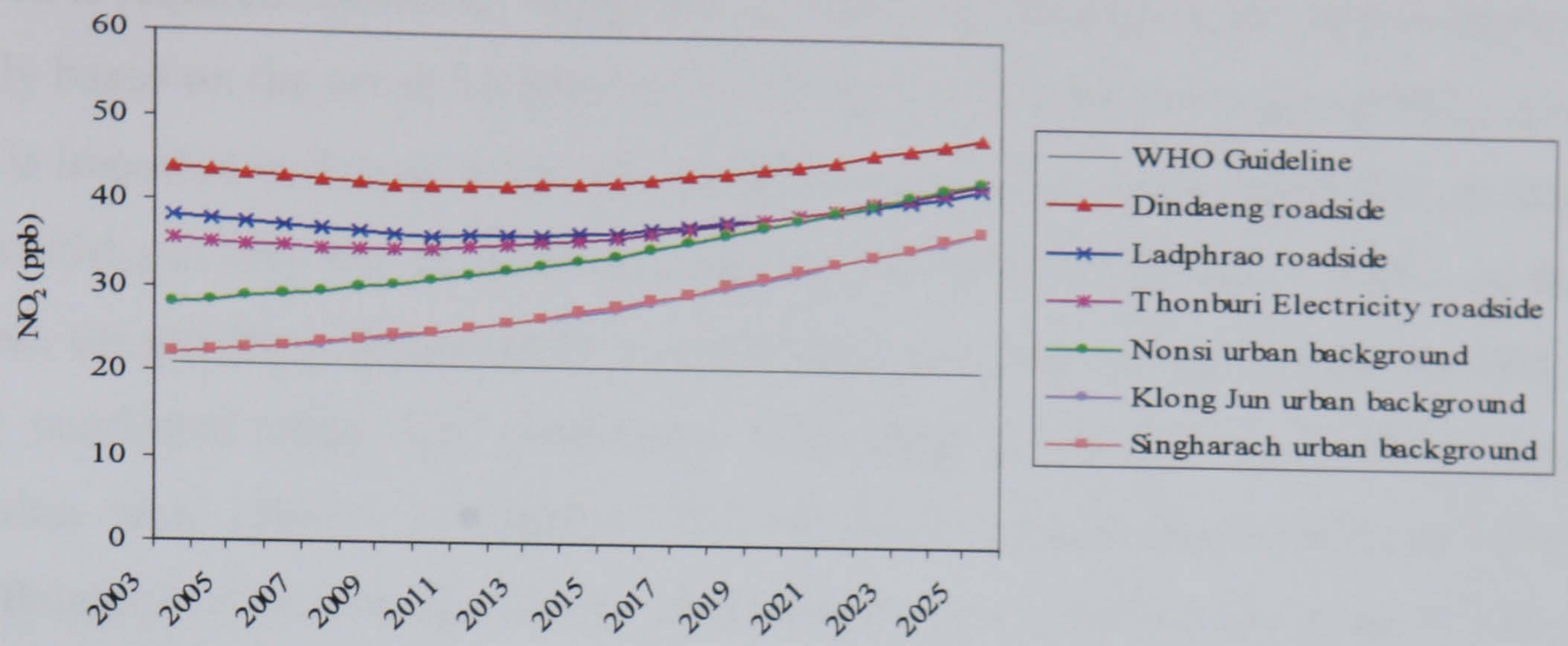


Figure 7.3 Projections of the annual mean NO_2 concentrations in Bangkok

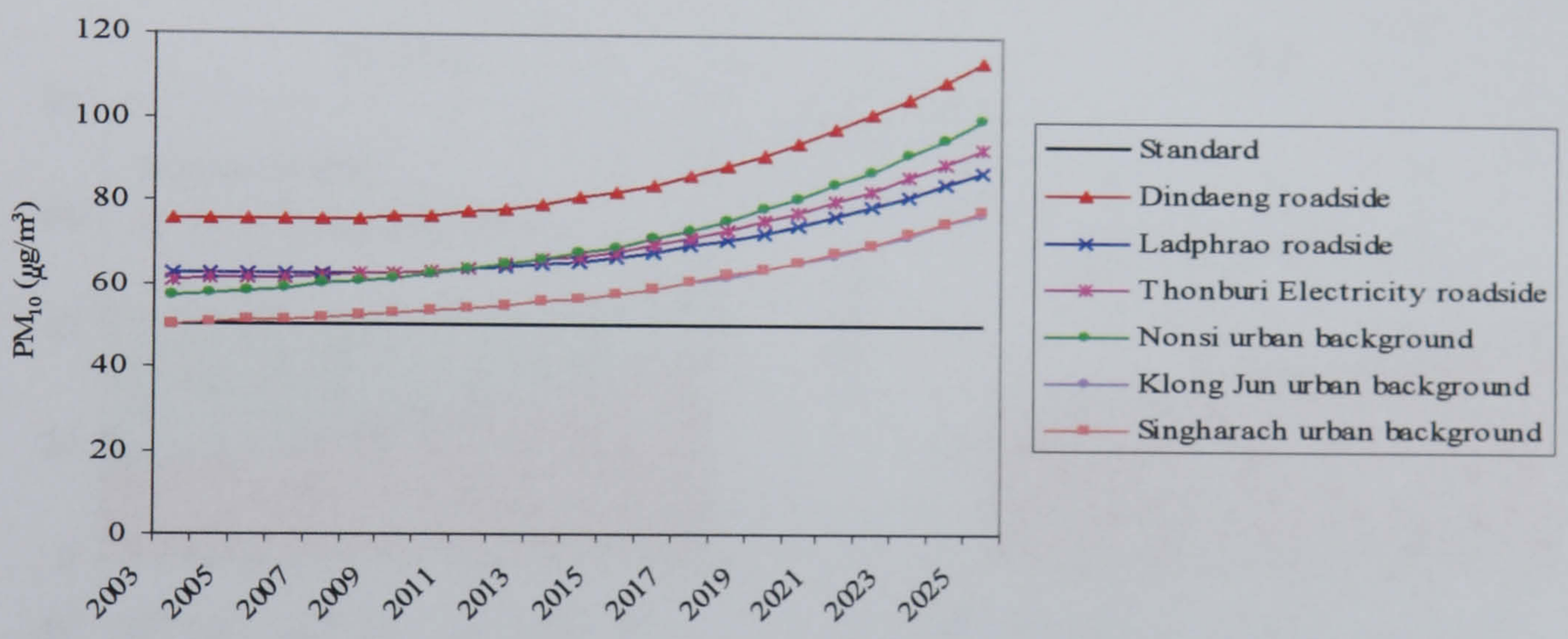


Figure 7.4 Projections of the annual mean PM_{10} concentrations in Bangkok

The Bangkok GRAM model can give the components contributing to air pollution. Dindaeng and Nonsi (see its details in Table 6.3) are shown, in this study, to be the worst locations, at roadside sites and urban background sites respectively, and were selected to study the contribution of NO_2 and PM_{10} which were projected by the Bangkok GRAM model. Figures 7.5 and 7.6 illustrate the continuous reductions of the road contribution at Dindaeng station in the future years. On the contrary, the figures show the constant increases of urban background concentrations at both the Dindaeng and Nonsi stations because a growth rate of 9% a year was assumed over the whole period. The figures show that the overall reduction at the Dindaeng roadside site in the first few years after 2003 is offset by the increase of the urban background contributions. The figures show the increase of overall levels of NO_2 and

PM_{10} at the two stations in future years. The figures suggest a great reduction of the urban background levels should be achieved if a rapid improvement in air quality in Bangkok is required. However, in the case of PM_{10}, the success of the improvement is not only based on the urban background contribution, but also the regional PM_{10} level which is imported to Bangkok from its suburban areas. The resuspended PM_{10} or non-exhaust PM_{10} is very low at the Dindaeng roadside station with heavy traffic. In this research, the emission factors of the resuspended dust were obtained from the TRL's survey conducted under UK conditions. These factors seem to be underestimated when they were applied in Bangkok. Future work to obtain these emission factors under Bangkok conditions should be undertaken, so as to obtain more accurate values of these factors and improve the validity of the Bangkok GRAM's predictions on PM_{10}.

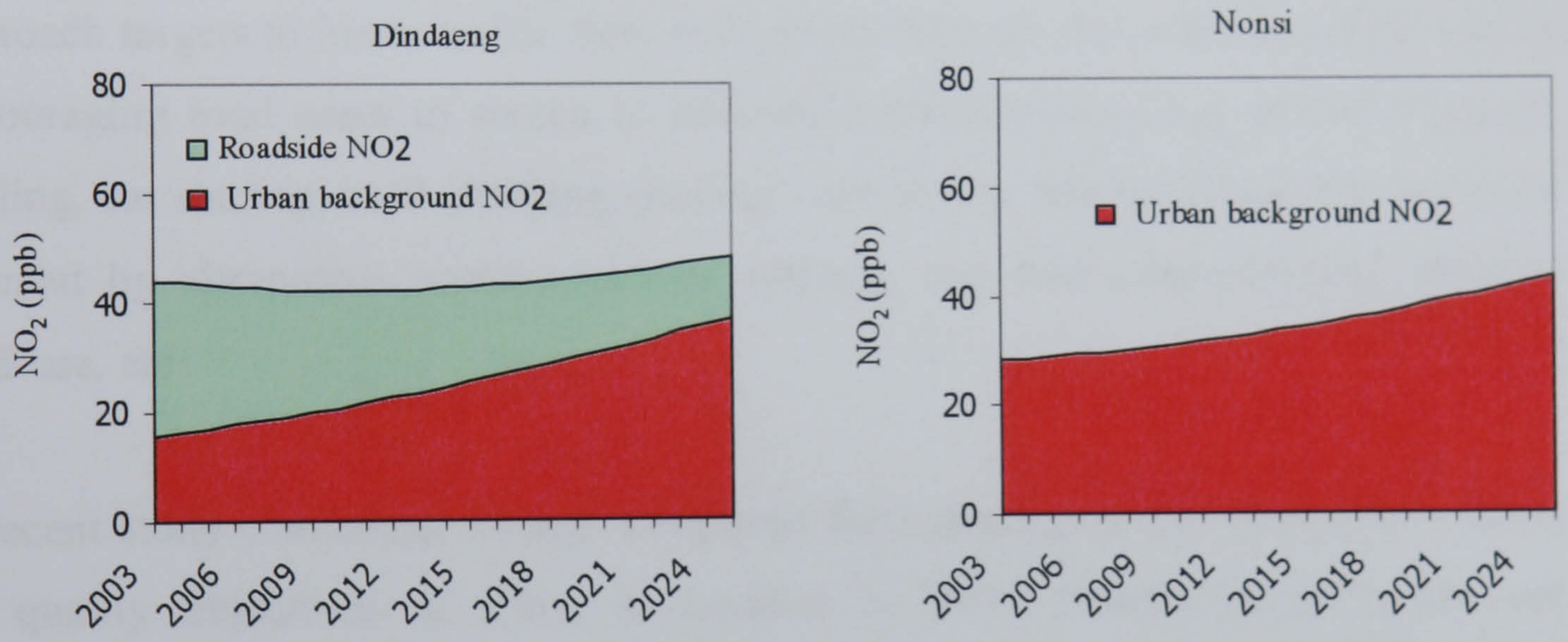


Figure 7.5 Projection of NO_2 contributions in Bangkok during 2003-2025

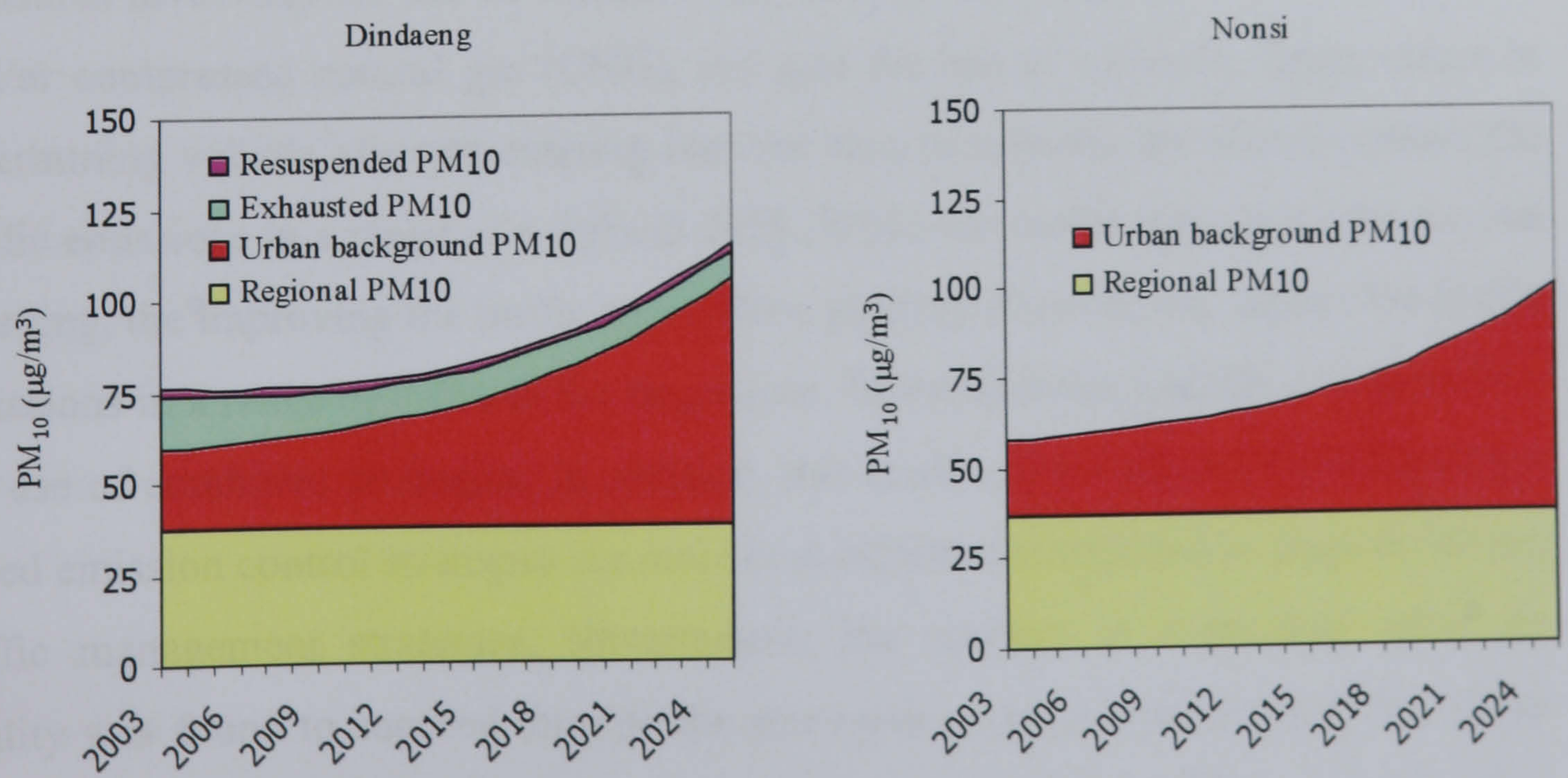


Figure 7.6 Projection of PM_{10} contributions in Bangkok during 2003-2025

7.4 Needs of additional measures on road transport emissions

In practice, strategies to reduce emissions from road transport comprise three approaches: the emissions reduction approach, the traffic management approach, and the combined approach (Mediavilla-Sahaguna and ApSimon, 2003). The emission reduction approach, the implementation of which can usually only be achieved by actions on a national scale, is the reduction of emissions per vehicle. It is based on emission reduction conducted through improving technologies of vehicle and emission control devices, e.g. fuel injection systems, computer control of engines, catalytic converters, or particle traps and improving fuel technology, e.g. unleaded petrol, low suphur diesel, oxyfuel, compressed natural gas (CNG), biofuel and fuel cells. The traffic reduction approach reduces total emissions from road transport activities. The implementation can be launched at a local scale. The traffic reduction approach targets to lower traffic flow and growth through the reduction of car use by encouraging road users to switch to alternative travel modes, e.g. public transport, cycling, car sharing, road charging, parking control, etc. and to reduce transportation demand by alternative communications systems, e.g. telecommunication, compact land-use, etc.

A recent study comparing a range of options for reducing traffic emissions to attain air quality objectives of PM_{10} in London in 2005 (Mediavilla-Sahaguna and ApSimon, 2003) estimated, from the base year of 1996, that the technology-base measures involving the use of cleaner fuels such as the liquid petroleum gas (LPG) and/or compressed natural gas (CNG), etc. and the use of emission limits values in determining vehicle allowed entering into the area of interest, are able to reduce the traffic emissions in a range of 4-36% in 2005. While the traffic measures such as road charging, the improving the traffic speed/flow, parking controls, etc. reduce the traffic emissions in a range of 0-6% in the target year. More emission reduction is gained by the use of combined strategies. In addition, this study estimated that the technology-based emission control strategies are more cost-effective compared to those involving traffic management strategies. Nevertheless, the success in improving urban air quality was found to succeed through the strategies under the umbrella of the traffic management and control activities. For example, the city of Bern and the Bern Canton, in the Bernstrasse/Zollikofen project undertaken in 1995 (EAUE, 2001), have adopted a traffic management programme based on three concepts through the

implementation of a steady traffic flow, the integration of all transport modes and a correspondingly suitable street design, and orientation towards a supply-orientated transport planning. The redevelopment concepts were locally differentiated according to the conditions on particular roads. This project succeeded in saving fuel consumption and emissions by about 15-25% compared with the undeveloped condition.

Because road transportation is increasing everywhere, improvements in technology may not be sufficient to counteract vehicle growth in future years. According to the results discussed above, it seems that the implementation of an emissions reduction approach is able to give a large number of traffic emission reductions over the short term. However for long term improvements, strategies based on the traffic management approach have to be implemented in combination with measures involving the emission reductions approach, otherwise it is not sufficient to fully address the problem of road transport emissions.

London-United Kingdom

Today, all newly registered vehicles in the UK must comply with the EURO III standards that came into force in 2000. EURO IV standards are already in place and will take effect in 2005/6, while additionally for heavy duty vehicles, EURO V standards are already in place to take effect in 2008 (DEFRA, 2004b). Aiming to achieve the Community's long term air quality aspirations, recently, the European Commission has initiated a series of consultation meetings aimed at defining EURO V (light duty vehicles) and EURO VI (heavy duty vehicles) limits to come into force around 2010 and 2013 respectively (DEFRA, 2004c).

There has been discussion in the UK negotiation whether EU Directive limit values will be achieved (DEFRA, 2004c). This discussion has considered existing measures to control transport emissions which have been agreed and which are included in the emission factors for mobile sources in the GRAM and Bangkok GRAM models. In addition discussions have started on emission factors beyond EURO IV, which are not yet included under existing measures and are still subject to negotiation. As the projections mentioned in previous section show, the UK will not meet EU air quality objectives for levels of NO_2 and PM_{10} at a number of urban areas and busy roads. It is

clear that more measures, national and /or EU measures, are required to improve air quality in a number of areas in the UK. Extra measures are not agreed in the EU but will be subject to negotiations. Among the additional measures discussed, the introduction of more stringent emissions controls was the greatest impact on air quality at background and roadside locations in 2020 of all measures considered and the early introduction of proposed vehicle emissions standards, the second most effective measure (DEFRA, 2004b). There have been suggestions that improvements in urban transport emissions of up to 30% may be achieved mainly through technology improvements (DEFRA, 2004b). If these are real then emission factors for future years in the GRAM model would need to be adjusted. The additional measures discussed in the UK negotiation also concern reductions in traffic activity, e.g. road charging schemes leading to overall 6% reduction in NO_x and PM_{10} exhaust emissions in urban areas (DEFRA, 2004b).

Bangkok-Thailand

In Thailand, the similar EU directive limit values are also implemented, but normally later than those in the UK by around two years or more, whilst the number and growth rate of vehicles in Bangkok is much greater than London's as detailed in Chapter 5. In addition to the more stringent emission limit measures to cut new vehicle emissions, the strategies under the emission approaches, such as the use of catalytic converters with new gasoline vehicles on 1 January 1993, unleaded gasoline throughout the country on 1 January 1996, diesel EURO III on 1 January 2004, gasohol (voluntary action), the use of periodic roadside inspections, and the annual inspection have been applied in Thailand (PCD, 2004d, 2004i). The Bangkok sky-train, a mass rapid transit system with a length of 23.5 km was in service at the end of 1999, and the 20 km underground train was in service on August 2004 (PCD, 2004d). The expansion of the mass transit systems may help in reducing the traffic growth rate and traffic flow in Bangkok. Under the current vehicle emission control policies in Thailand, in the future years NO_x and PM_{10} concentrations, as shown in Figures 7.3 and 7.4, are still exceeding their guidelines or standards. The additional measures for the reduction of NO_x and PM_{10} levels in Thailand are apparently still needed in the same way as in the UK.

7.5 Assessment of additional strategies to reduce NO_2 and PM_{10} in Bangkok

In this research, a number of strategies to reduce NO_2 and PM_{10} in Bangkok were proposed, and we used the Bangkok GRAM model as the tool to quantify the effectiveness of the strategies. Regarding the capability of the model we considered idealised strategies based on (1) the traffic approach, in a single strategy as the traffic flow reduction, and as a combined strategy involving the reduction of traffic flow (F), traffic growth (G/GI), and the traffic speed (SP/SPI), and (2) the combined approach as the reduction of traffic flow (F), traffic growth (G/GI), and traffic speed (SP SPI), and the emission density (E) over the area of interest. The description of strategies is shown in Tables 7.1 and 7.2 for the roadside and urban background sites respectively.

Due to the simplicity of the Bangkok GRAM model, the emission reduction through the emission approach cannot specify in detail strategies such as 50% of buses and trucks in Bangkok converted to CNG, but the assumption was based on the total emission density reduction which can be implemented through the conversion to cleaner fuels of current vehicles, and/or the introduction of more stringent traffic emissions controls to new vehicles, and/or the early introduction of proposed vehicle emissions standards. The Dindaeng roadside station and Nonsi urban background station (see its details in Table 6.3) were selected for testing the strategies.

When the strategies as shown in Table 7.1 were applied to the Dindaeng roadside site, and in Table 7.2 to the Nonsi urban background site in year 2006, the reduction scenarios of NO_2 and PM_{10} are shown in Figures 7.7 and 7.8 respectively. The percentage of concentration reductions at Dindaeng and Nonsi stations in 2006, 2010, 2015, 2020, and 2025 are summarized in Table 7.3.

Table 7.1 Description of the strategies at the roadside station

Strategy	Description
F1G9	Reduction of base-year traffic flow, 1% a year + traffic growth rate 9% a year (base year)
F2G9	Reduction of base-year traffic flow, 2% a year + traffic growth rate 9% a year (base year)
F3G9	Reduction of base-year traffic flow, 3% a year + traffic growth rate 9% a year (base year)
F2G8	Reduction of base-year traffic flow, 2% a year + traffic growth rate to 8% a year
F3G8	Reduction of base-year traffic flow, 3% a year + traffic growth rate to 8% a year
F2G7	Reduction of base-year traffic flow, 2% a year + traffic growth rate to 7% a year
F3G7	Reduction of base-year traffic flow, 3% a year + traffic growth rate to 7% a year
F2GI7	Reduction of base-year traffic flow, 2% a year + incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025
F3GI7	Reduction of base-year traffic flow, 3% a year + incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025
F2GI7SP1	Reduction of base-year traffic flow, 2% a year + incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025 + increase of base-year vehicle speed, 1 km/h a year
F3GI7SP1	Reduction of base-year traffic flow, 3% a year + incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025 + increase of base-year vehicle speed, 1 km/h a year
F3GI7SP1E10	Reduction of base-year traffic flow, 3% a year + incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025 + increase of base-year vehicle speed, 1 km/h a year + reduction in emission density ;90% of base year emission density during 2006-2010, 80% during 2011-2015, 70% during 2016-2020, and 60% during 2021-2025
F3GI7SP1E20	Reduction of base-year traffic flow 3% a year + incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025 + increase of base-year vehicle speed, 1 km/h a year + reduction in emission density; 80% of base year emission density during 2006-2010, 70% during 2011-2015, 60% during 2016-2020, and 50% during 2021-2025)
F3GI7SP1E30	Reduction of base-year traffic flow 3% a year + incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025 + increase of base-year vehicle speed, 1 km/h a year + reduction in emission density; 70% of base year emission density during 2006-2010, 60% during 2011-2015, 50% during 2016-2020, and 40% during 2021-2025)

Table 7.2 Description of the strategies at the urban background station

Strategy	Description
G8	Reduction of base-year traffic growth rate 9% to 8% a year
G7	Reduction of base-year traffic growth rate 9% to 7% a year
GI7	Incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025
GI7E10	Incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025 + reduction in emission density ;90% of base year emission density during 2006-2010, 80% during 2011-2015, 70% during 2016-2020, and 60% during 2021-2025
GI7E20	Incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025 + reduction in emission density; 80% of base year emission density during 2006-2010, 70% during 2011-2015, 60% during 2016-2020, and 50% during 2021-2025)
GI7E30	Incremental reduction in traffic growth rate; 7% during 2006-2010, 5% during 2011-2015, and 3% during 2016-2025 + reduction in emission density; 70% of base year emission density during 2006-2010, 60% during 2011-2015, 50% during 2016-2020, and 40% during 2021-2025)

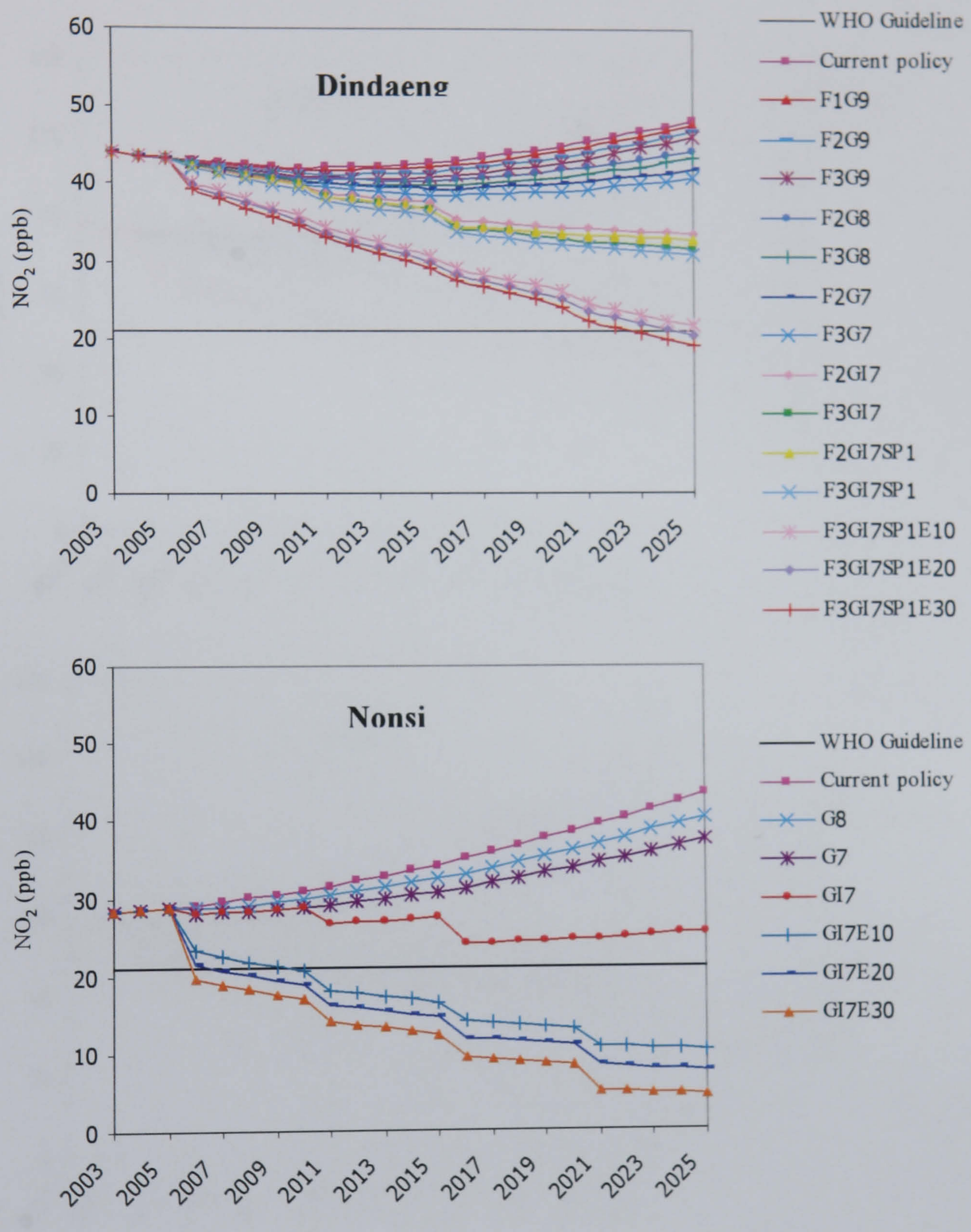


Figure 7.7 Scenarios on NO_2 reduction in Bangkok during 2003-2025

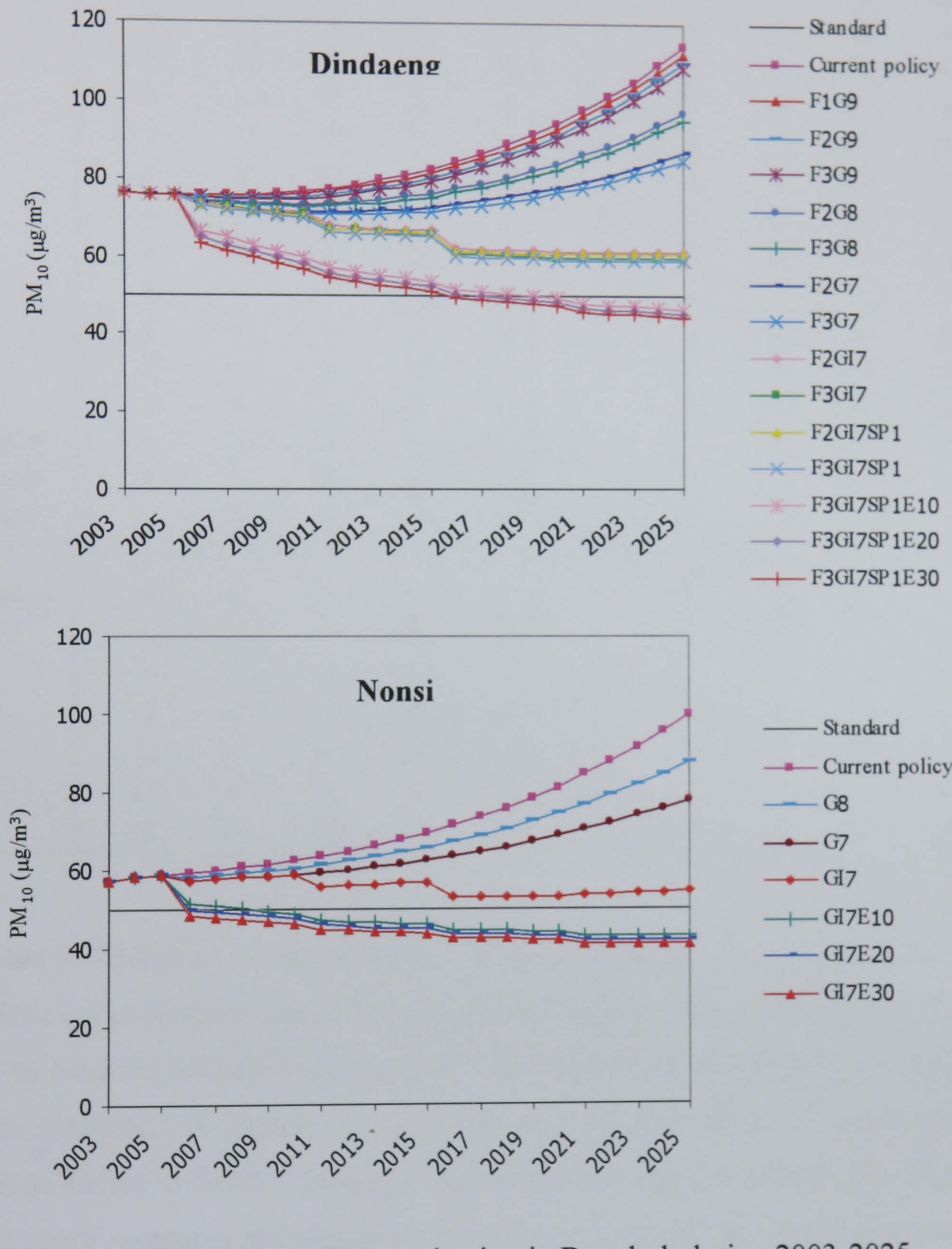


Figure 7.8 Scenarios on PM_{10} reduction in Bangkok during 2003-2025

Table 7.3 Percentage of NO_2 and PM_{10} reductions at Dindaeng and Nonsi stations in 2006, 2010, 2015, 2020, and 2025

Strategy	% reduction in NO_2 concentration					% reduction in PM_{10} concentration				
	2006	2010	2015	2020	2025	2006	2010	2015	2020	2025
Dindaeng										
Current policies	3	5	3	-2	-10	0	-1	-8	-24	-50
F1G9	3	5	4	0	-8	1	0	-7	-22	-48
F2G9	3	6	6	1	-7	1	1	-6	-20	-45
F3G9	3	7	7	3	-5	1	2	-4	-18	-43
F2G8	3	7	8	5	-1	2	4	0	-11	-28
F3G8	4	8	10	7	1	2	4	1	-9	-26
F2G7	4	9	11	9	5	3	6	4	-3	-14
F3G7	4	10	12	11	7	4	7	6	-1	-12
F2GI7	4	9	15	22	24	3	6	12	19	19
F3GI7	4	10	17	25	28	4	7	13	21	21
F2GI7SP1	4	10	16	24	25	4	7	13	20	20
F3GI7SP1	5	10	18	27	30	4	8	14	22	22
F3GI7SP1E10	9	19	30	41	51	12	21	29	35	39
F3GI7SP1E20	10	20	32	43	53	15	23	31	36	40
F3GI7SP1E30	11	22	34	45	56	17	25	33	38	42
Nonsi										
Current policies	-4	-10	-21	-37	-54	-3	-9	-20	-41	-74
G8	-2	-6	-15	-28	-43	-2	-5	-14	-29	-53
G7	0	-2	-9	-20	-33	0	-2	-8	-19	-36
GI7	0	-2	3	13	10	0	-2	1	7	5
GI7E10	18	27	41	53	64	10	15	20	23	25
GI7E20	24	33	48	61	73	13	17	22	25	27
GI7E30	30	40	56	70	84	16	19	24	27	29

In the case of Dindaeng roadside station, the NO_2 and PM_{10} concentrations have to reduce their concentrations from the base year by around 47% and 34% respectively in order to meet its guideline or standard. The scenarios from the Bangkok GRAM model as illustrated in Figures 7.7 and 7.8, and the percentage of concentration reduction as shown in Table 7.3 suggest that to improve the level of NO_2 and PM_{10} in this area, more measures are needed to be added to the current emission reduction policies. The reduction of traffic activity, as much as in the strategies of F2GI7 and F3GI7, can reduce the concentrations of NO_2 and PM_{10} but large exceedence still exists. The model suggests that under the current situation at the Dindaeng site, the reduction of traffic activities gives an effective improvement in the long term or when the small improvement is required in short term. The model also suggests, through the last three strategies, that the guideline or standard will be achieved at this location

before 2025 only if more emission reduction is introduced to the vehicle fleet in Bangkok, or specified low emission vehicles are allowed passing this location (on the other hand, high emission vehicles are prohibited passing this location).

NO_2 and PM_{10} concentrations at the Nonsi urban background station located in the central zone will meet its guideline and standard if their base year levels are reduced by around 26% and 13% respectively. The scenarios from the Bangkok GRAM model as illustrated in Figures 7.7 and 7.8, and the percentage concentration reduction as shown in Table 7.3 reveal that the reduction of traffic growth rate cannot reduce the annual mean NO_2 and PM_{10} concentration to achieve their guideline or standard. The guideline or standard will be met at this site sooner than that at Dindaeng roadside site. For example, if the GI7E30 measure is implemented in 2006, the guideline or standard will be achieved at Nonsi site in that year.

Hence, it can be concluded that over the period of 2006-2025 the emission approach is an essential strategy for improving the air quality in Bangkok. Due to the capability of the Bangkok GRAM model in giving the composition of pollution contribution as shown in Figures 7.5 and 7.6, this helps one decide which of the sources contributing should attention be focused upon. For example, when the component contributions to the concentrations of the annual mean NO_2 under the F3GI7SP1E30 and GI7E30 scenarios at the Dindaeng and Nonsi stations respectively (Figure 7.9) were identified, the model gives an estimate showing that the introduction of the GI7E30 strategy on the current policy at Nonsi site will reduce the annual mean NO_2 to meet its guideline after the first year (2006) of the introduction. The F3GI7SP1E30 strategy applied to Dindaeng site was predicted to reduce the background concentration below its guideline, but not enough to decrease total contribution (road contribution and background contribution) to meet the guideline. The predictions from the model suggests that more measures should be added over and above the F3GI7SP1E30 strategy and its focus should be to decrease the road contribution NO_2 in order that the total NO_2 will meet the guideline earlier than the year 2023.

It shall be remarked that the emission reduction approach proposed in this research is based on the assumption of the conversion of current vehicles to cleaner, and/or the introduction of more stringent traffic emissions controls to new vehicles, and/or the

early introduction of the proposed vehicle emissions standards. Thus the reduction will not only effect the reduction of the emission density, but also the exhaust emission rates. If the emission factors for the future years in the Bangkok GRAM model are adjusted, the reduction rate of road contribution will be higher than that shown in the prediction. In the same way, the standard or guideline will be achieved earlier than is estimated in Figure 7.9.

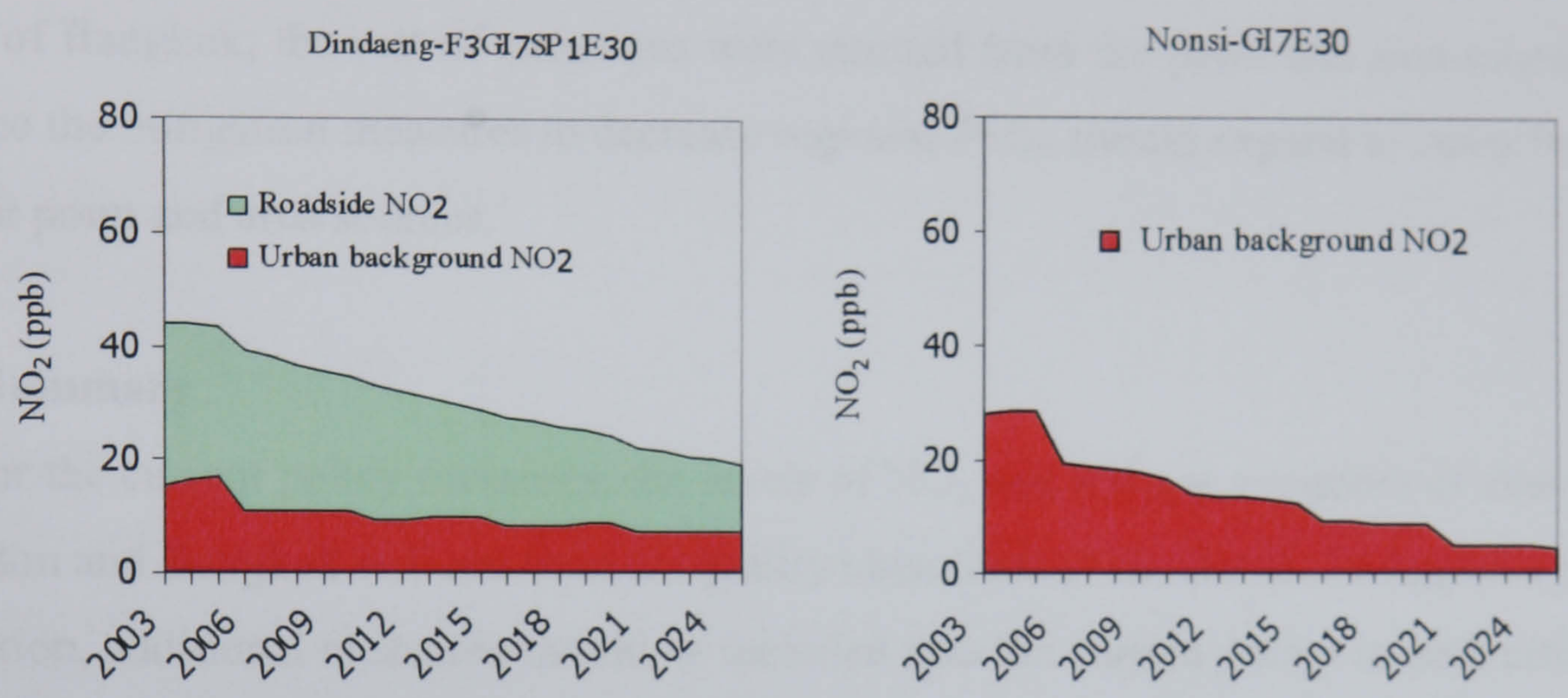


Figure 7.9 Projections of NO_2 contribution in Bangkok under the F3GI7SP1E30 and GI7E30 strategies

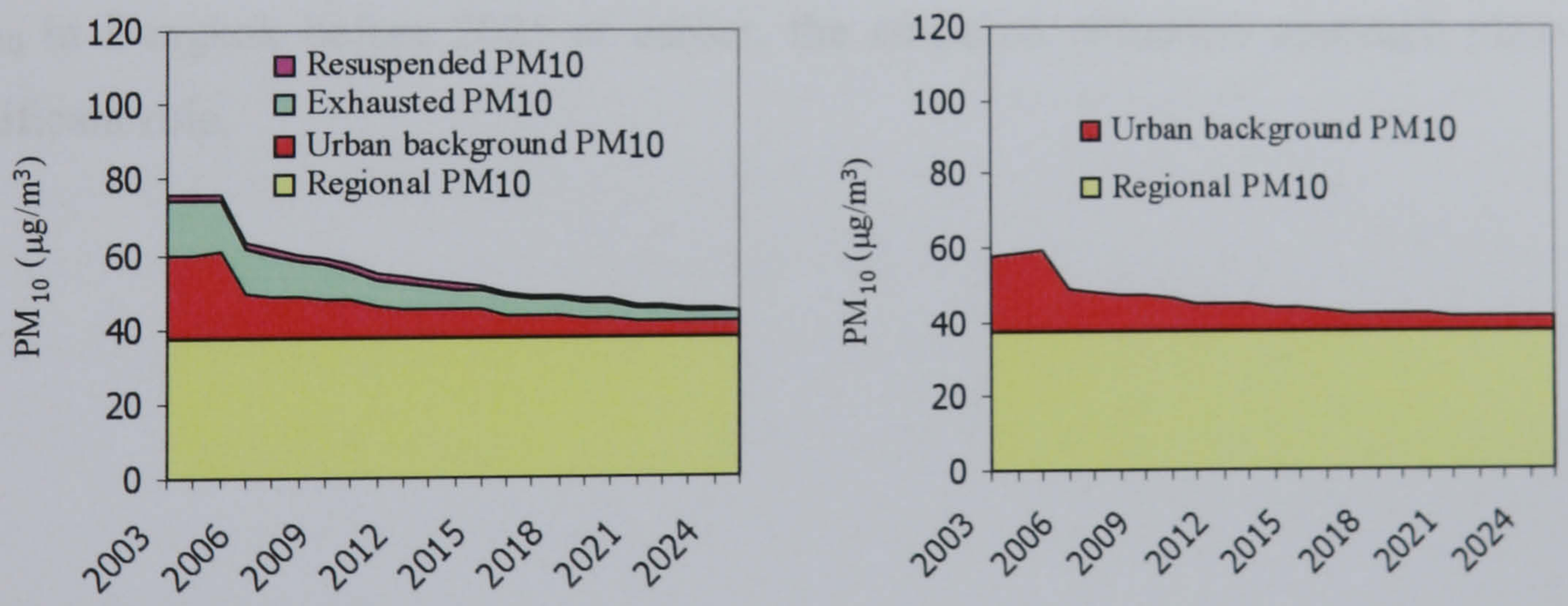


Figure 7.10 Projections of PM_{10} contribution in Bangkok under the F3GI7SP1E30 and GI7E30 strategies

In the case of PM_{10} as seen in Figure 7.10, the model can be used to identify the contribution at roadside and urban background sites of four and three components respectively. It can be seen that after the introduction of additional measures based on the F3GI7SP1E30 or GI7E30 strategies to the current policy, all the contributions reduce to be the minor components, leaving the regional PM_{10} as the major

component of PM_{10} at both roadside and urban background locations in the future years. In order to accelerate the improvement of air quality in Bangkok, the predictions suggest that the decision maker should launch the mitigation measures on PM_{10} reduction not only in Bangkok area, but also in its surrounding area, so as to lower the level of regional PM_{10} entering to Bangkok area. According to the study of the emission inventory in Chapter 5, the study indicated that the mobile source contribution was around 54-55% of the total emissions of NO_2 and PM_{10} in suburban area of Bangkok; the rest of emissions were emitted from the point and area sources. Hence the mitigation measures to decrease regional PM_{10} should expand to cover both of the point and area sources.

7.6 Summary

Under the current policy measures, the levels of NO_2 and PM_{10} at a number of sites in London and Bangkok will not meet air quality objectives or standards. To improve the situation, additional measures should be included into the current policy in both cities. The Bangkok GRAM model can provide preliminary assessments of the scale of effectiveness of strategies based on the traffic management approach and emission reduction approaches. In order to achieve the guidelines or standards of NO_2 and PM_{10} in Bangkok before 2025 or earlier, the emission reduction approach plays a significant role.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

This thesis demonstrates a simple, risk-based approach to urban air quality policy. Urban air quality management requires knowledge of emissions, models and measurements depending on various degrees of complexity. This thesis has tested whether a screening approach originally developed for the UK could be applied and adapted to other cities around the world. It has been shown that it can produce agreement with measurements consistent with other multi-source dispersion models (See Table 2 from Fisher (2004b)). The screening model does not give directly a mapping capability but it does allow policy options to be easily evaluated. One reason why the mapping capability has not been developed is that the best ways of incorporating urban meteorology into dispersion models have not been established as yet (Fisher, 2004b), though this is a very active field. Hence a simple approach based on tests against measurements has been adopted. Future models may be able to treat urban meteorology in more physically realistic ways.

Two cities, London and Bangkok, have been investigated in detail. Adjustments to key factors used when the model was applied to London, have been made in order to apply the model to Bangkok. The key parameters include wind speed, proportion of light winds, photochemical reaction rates, emission factors etc. It is found that as long as the key parameters are given appropriate, representative values, the screening model can be applied to Bangkok, and presumably other cities. This means that screening models of this type can be applied in a variety of situations circumventing the need for very detailed data before deciding on air pollution policy.

A new air quality model called the Bangkok GRAM model was modified from a screening line source air quality model developed in the UK. The new model has been extensively tested. The method is easy to apply and could be adopted by policy makers. Policy makers could run the models themselves. Even though the future air quality in urban area can be mapped, detailed mapping is not necessary to determine if an exceedence is likely to occur. The two cities face similar problems. Differences

in meteorology and photochemistry are small. It is a somewhat unexpected result that the models of the two cities behave similarly. One might have anticipated larger differences.

Studies on NO_2 and PM_{10} concentrations in London suggest that objectives will not be achieved, which is consistent with the results of the Bangkok GRAM model. It will be difficult to find a solution to traffic related air pollution problems in very large cities. Air quality targets will be hard to achieve. One may have to accept that the improvement will not be as rapid beyond 2010 as has been hoped for. It appears that the only solution is through strict controls on traffic emission and activity, which may not meet with public acceptance in either London or Bangkok.

8.1.1 Selection of the screening line source air quality models using in the UK

There are no standards for air quality models. They are judged according to their agreement with measurements. The advantages of simple models are (1) they are easy to apply, (2) one can test their sensitivity to changes in the main parameters, (3) policy outcomes are simple to evaluate, (4) one can readily perform sensitivity studies and multiple runs, and (5) many scenarios can be investigated. Screening models are easy to set up and use. They can be applied to cities for which only limited data are available. Such models can be transferred to non-experts without the need to rely on consultants. This is why this kind of model is being considered in this application.

The CAR, DMRB, LEZ, and GRAM models were studied using descriptions of the models, and were assessed against criteria. The DMRB and GRAM models showed the possibility of modification for application in Bangkok. For the predictions of the NO_2, CO, and PM_{10}, the GRAM model gives better performance than predictions of the DMRB model at the roadside in London. The DMRB model performs better than the GRAM model at the Marylebone Road site for C_6H_6 predictions. In Bangkok, the performance of the GRAM model at the roadside sites is better than the DMRB model for the predictions of the NO_2 concentration, and for CO, whereas the DMRB model performs better in the case of the PM_{10}. The DMRB model needs a regional model (or measurements) for predicting the future urban background levels, while the GRAM model does not. The formulae and all factors in the GRAM model are known and changeable to fit with other local conditions, whereas some of the DMRB

formulae have limitations. Hence the GRAM model was selected for modification to an air model for assessing air quality in Bangkok. The NO_2 and PM_{10} levels in Bangkok are of major concern.

8.1.2 Description of the GRAM model

The model is based on algorithms used in the CALINE4, and R91 models, and incorporates the DMRB's vehicle emission factors, year correction factors, and vehicle speed correction factors. The total concentration is derived from the summation of the predicted roadside and the predicted background concentrations. The predictions of the road contribution involve the calculation of the "Effective LDV and HDV fraction", the "Relative roadside concentration", and the "Traffic flow in the year of interest". The calculations of the urban background concentrations consist of the "Emission in the present year", the "Urban diameter" and the "Urban emission factor change". The observed urban background levels were not consistent with predictions because of the model's concept of a uniform concentration throughout the urban area. The internal parameters assumed to be different between two cities, are the wind speed, the NO_2/NO_x empirical relationship, the NO_2/NO_x theoretical relationship, which relate to the ambient temperature; the background ozone; and the primary NO_2 from mobile sources, the fraction of mobile sources, and the DMRB's year correction factor. The model suggests that the road contributions of NO_2, CO, C_6H_6, and PM_{10} can be reduced through the reduction in traffic flow, the reduction in the fraction of high duty vehicles (but not for the case of CO) in the vehicle fleet, and the increase in traffic speed to a limit that is no faster than 100 km/h. The traffic data, the emission density, and the regional background PM_{10} are the input data, but detailed studies are needed.

8.1.3 Bangkok conditions

Traffic growth over the last ten years was about 20% in London, and greater than 100% in Bangkok. The fraction of heavy duty vehicles was 0.12 and 0.03 in London and Bangkok respectively. The annual mean wind speed, an internal parameter in the GRAM model, is 3 m/s, while it was around 2 m/s in Bangkok. A new empirical equation for the NO_x and NO_2 relationship (NO_2 Option 1) conducted under Bangkok conditions gives better predictions ($R^2 = 0.9161$). The relationship based on the photochemical approach (NO_2 Option 2) predicts lower NO_2 than the observations

because the GRAM model set the temperature 15°C for a calculation in London, whereas it was around 30°C in Bangkok. The fraction of primary NO_2 from mobile source is 0.05 in the model, whilst it was around 0.16 in Bangkok. The fraction of NO_x and PM_{10} emitted from mobile sources was 0.7 in London and 0.9 in Bangkok. The year 1999 emission density of NO_x in London was 0.07 kt/km^2/y. It was about half of the Bangkok emission densities for the years 1997-2002, which was about 0.12 kt/km^2/y. The density of PM_{10} in Bangkok was 6 t/km^2/y, which was double London's value. The averaged regional background PM_{10} was about 15 μg/m^3 in the UK and 37 μg/m^3 in Bangkok. The reduction rate of road transport emissions in Bangkok was not as fast as estimated in the DMRB's year correction factor. Around 20-25% of road contribution PM_{10} in Bangkok was attributed to resuspended dust.

8.1.4 Development, performance and sensitivity of the Bangkok GRAM model

In the development of the Bangkok GRAM model, the winds, the relationship between NO_x and NO_2, the urban background concentration, and the year correction factors have been changed. The prediction of urban background concentration was changed from the assumption of a uniform concentration throughout the urban area to different concentrations between a central, an inner, and an outer zone. The typical emission density values of the inner and central zones are twice and three fold, respectively, those of the outer zone. The emission factors of the resuspended dust were obtained from the TRL Environment Group data. The values of 0.01 and 0.09 g/km are for the light duty vehicle and heavy duty vehicles respectively. They have been included in the prediction of the road contributions. The uncertainty of the predictions in the model is well within the requirements for air quality models given in the EU first Daughter Directive. The variation of all factors influences the model predictions. Predictions of NO_x and PM_{10} are very sensitive to changes in the wind speed. The fraction of heavy duty vehicles (HDV fraction) is also very sensitive to NO_x prediction.

8.1.5 Assessment of air quality in London and Bangkok

Projections of the emissions of NO_x and PM_{10} in the UK urban areas show decreases in future years due to the penetration of newer vehicles meeting more stringent emission limit values. Similar trends arise in Bangkok but the decrease is very slight.

Projections of the UK urban NO_2 and PM_{10} concentrations during 2002-2010, by a range of methods, indicated that exceedences would exist at many roadside sites and some background sites in London. The Bangkok GRAM model projections of NO_2 and PM_{10} concentrations at the roadside sites and urban background sites in Bangkok indicated that the levels of the two pollutants will continue to exceed its guideline or standard and become higher in later years. There has been discussion in internal UK negotiations whether EU Directive limit values will be achieved. This discussion has considered existing measures and included emission factors beyond EURO IV. From the projections, it is clear that more measures are required to improve air quality in a number of areas in the UK. Among the additional measures discussed, the introduction of more stringent emissions controls has the greatest impact in 2020 of all the measures considered and the early introduction of proposed vehicle emissions standards the second most effective measure. These measures have been suggested in order to reduce urban transport emissions by up to 30%. At a very heavy traffic roadside site in Bangkok, the NO_2 and PM_{10} concentration have to be reduced by around 47% and 56% respectively, in order to meet their guidelines or standards. The Bangkok GRAM model suggests that a reduction of 2-3% in traffic flow in combination with the reduction of traffic growth rate to 7%, 5%, and 3% during 2006-2010, 2011-2015, and 2020-2025 respectively can maintain a continuing reduction, but the large exceedence will still exist. The model shows that more improvement can occur with the introduction of more stringent emission control on vehicles, or the early introduction of proposed vehicle emissions standards.

8.2 Recommended future work

London now has more monitoring sites, so more extensive testing of the model is possible. One could consider alternative emission factors representing more advanced technology EURO V and beyond, and hybrid vehicles. More measurements are needed to understand better particulate resuspension in the UK. The measurement of nitrate particulate and other semi-volatile compounds in particulate matter within different size ranges as a long-term average in Bangkok, is recommended. The resuspended emission factors of the light duty vehicles and heavy duty vehicles under Bangkok environments should be undertaken. The predictions of the Bangkok GRAM model should include CO and HC, and the short term average of NO_2 and PM_{10} in later versions.

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Appendix 1

A1.1 PM_{10} level at Thonburi Electricity station

The PM_{10} at Thonburi Electricity station was not included in the calculation of the correction factor for the roadside site in Bangkok due to its unusual features. Thonburi Electricity station is located on the Intrapituk Road for which the traffic flow was around 65000 vehicle/day in 2003. The BAM is housed in an air-conditioned container and its inlet is on the top of the container. The GHV is collocated on the top on the BAM container. The station is standing at ground level in front of a building of Thonburi Tai transmission station under the operation of the Metropolitan Electricity Authority-MEA (MEA, 2001). MEA receives high voltage electricity from the Electricity Generating Authority of Thailand (EGAT) through 13 transmission stations. At a transmission station, the high voltage is reduced from 230 kV to a voltage of 115 kV or 69 kV and distributes electricity to substations along 69 power lines (MEA, 2001). Hence, this air quality monitoring station is surrounded by many power lines from the Thonburi Tai transmission station.

It was found that the PM_{10} levels observed at this station did not agree with the observations at the other roadside sites in Bangkok and elsewhere, as mentioned in Chapter 5. The observations at the other roadside sites show that the GHV-PM_{10} were almost twice the BAM-PM_{10}, but the PM_{10} levels measured by the GHV at Thonburi Electricity station were close to those of the BAM and surprisingly the seasonal average BAM-PM_{10} at this station was highest compare to the observations at the other stations in the same season as shown in Figures A1.1. This suggests little loss occurred in the BAM at this station. The relationship between the BAM-PM_{10} and the GHV-PM_{10} is shown in Figure A1.2. The ratio of GHV/BAM at this station over the period of 2001-2003 is shown in Figure A1.3 and the average ratio was 1.12 ± 0.26. In general, the ratio was even closer to 1.0 than those are observed at urban background sites.

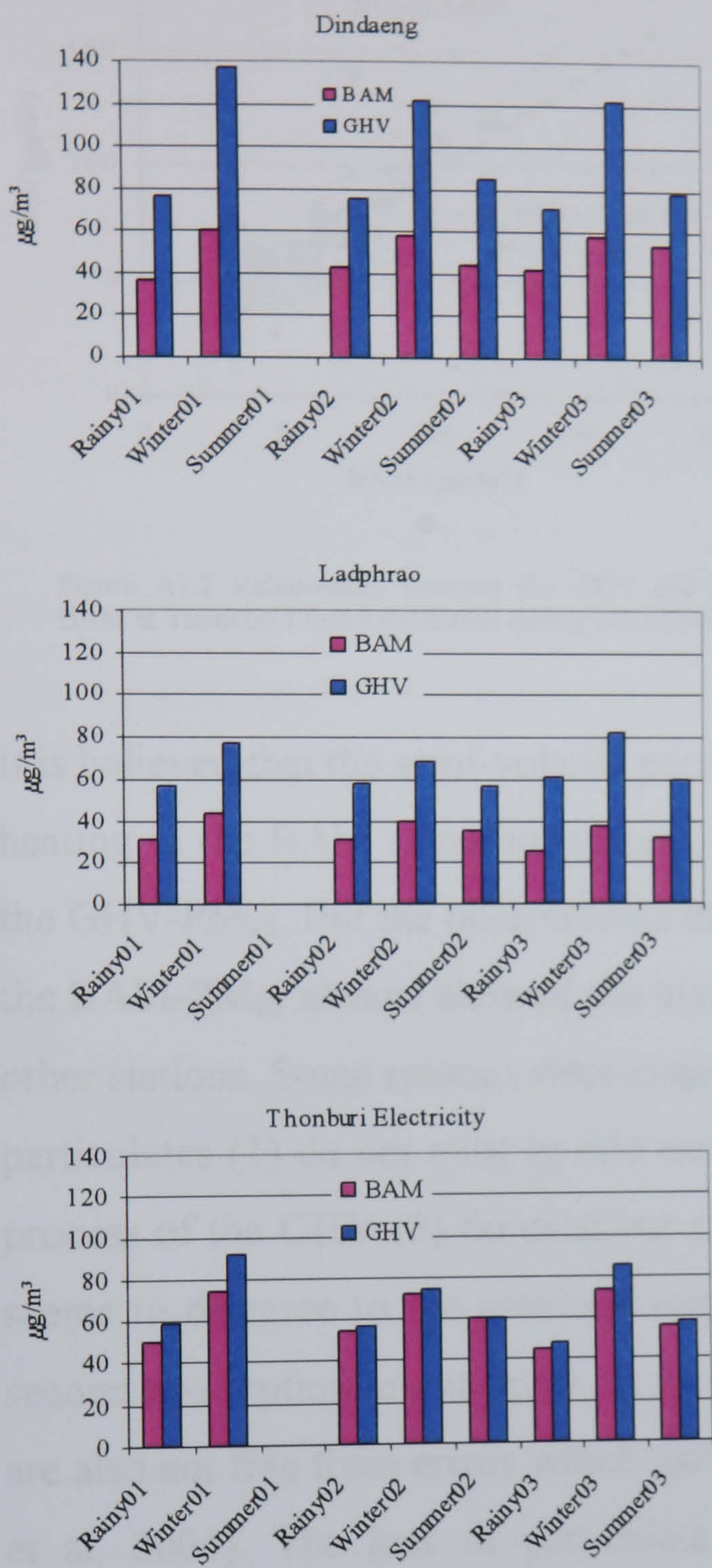

Figure A1.1 Seasonal average of the BAM-PM_{10} and the GHV-PM_{10} in Bangkok during 2001-2003

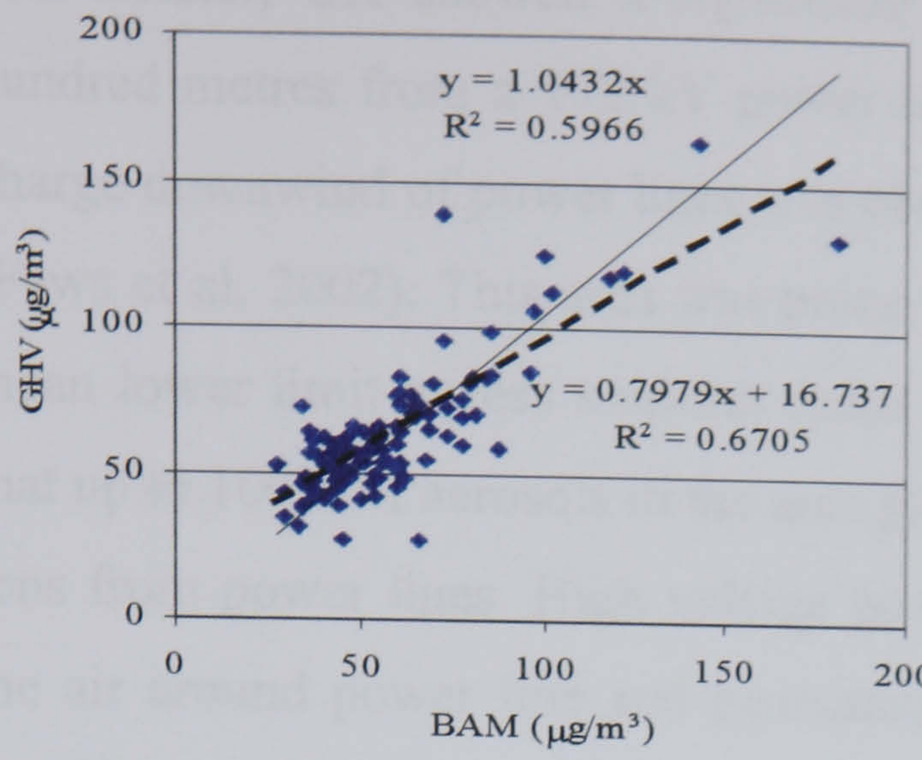

Figure A1.2 Relationship between the GHV and the BAM at Thonburi Electricity station during 2001-2003

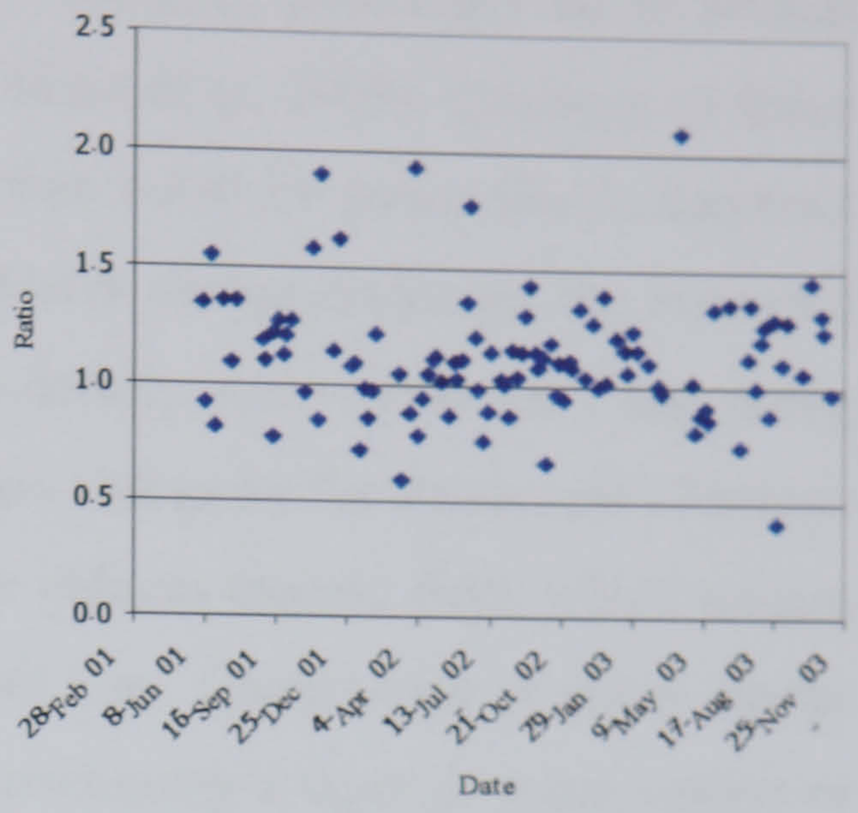

Figure A1.3 GHV/BAM ratio at Thonburi Electricity station during 2001-2003

It is believed that the semi-volatile particulate, mainly ammonium nitrate is lost due to heating in the BAM sampling system. So, the BAM-PM_{10} was found to be less than the GHV-PM_{10}. But the observations of the two methods at this station were close and the BAM-PM_{10} always showed the highest values comparing to those observed at the other stations. Some reasons were considered for this unusual result; that semi-volatile particulates (1) do not exist in this area, (2) do exist but are lost during the sampling process of the GHV (3) do exist but change to the other forms. The first assumption seems to disagree to the previous work and observation found in this research. The second assumption might occur, as mentioned previously that the filter-based methods are also not free from errors which may occur during and after the collection (Charron et al, 2004). The loss of particulate mass in this case seems to come from the volatilisation of semi-volatile components. However this assumption seems not be the plausible answer because the remaining PM_{10} levels in both methods at Thonburi Electricity station was higher than the BAM-PM_{10} observed at Dindaeng and Ladphrao stations. This suggests a lot of mass concentrations could survive in the BAM at Thonburi Electricity station. The last assumption seems to serve as a main probable explanation because (1) the PM_{10} levels given by both methods were in a range of PM_{10} found at the other roadside sites, and (2) both methods always gave systematically a similar pattern of observed mass concentration, and (3) a higher PM_{10} remains in the BAM compared with elsewhere.

As the location of this air quality monitoring station is surrounded by a lot of power lines, it is assumed that a strong electric field exists at this location. An investigation

near Bristol, UK showed a significant aerosol charging, potentially up to several hundred metres from a 132 kV power line (Wilding et al, 2000). Evidence of space charge downwind of power lines was observed near a 400 kV power line in Somerset (Fews et al, 2002). This area was prone to excessive corona discharge, the estimated mean lower limit excess unipolar space charge density was ~ 6000 cm^{-3}, suggesting that up to 100% of aerosols in the area gain excess charge by the attachment of corona ions from power lines. High voltage power line induces electric field, which ionizes the air around power line and generating corona ions. Corona ions of either charge rapidly nucleate nano-particles of 1-4 nm, by condensing a layer of water vapour or trace pollutant gases (Wilding et al, 2000). A proportion of the ions will remain in the nano-particle mode, while the others will attach to and charge up the existing pollutant aerosols in the air. A separation of charge (unipolar) will occur due to the relative mobilities of the electrons and the positive ions in the high field region surrounding the cables (Wilding et al, 2000). The separated cloud of positive or negative charges is called a 'space charge' (Henshaw, 2002). Ultimately, unipolar charging aerosol reverts to normal (bipolar) charge distribution (Withers, Foot, and Clark, 1998, Henshaw, 2002). Even if the power line reabsorbs the majority of these charges, substantial fluxes are potentially emitted into the atmosphere (Henshaw, 2002). From this brief review, it seems likely that a relatively highly charged atmosphere exists around the Thonburi air quality monitoring station.

It has been found that bipolar charged particle could agglomerate in the alternating electric field of 5.0 kV/cm and within a resident time of few seconds (Laitenen et al, 1996, Ji et al, 2004). This concept was initially introduced to improve the efficiency of the conventional electrostatic precipitator (ESP) systems. Agglomeration is a process in which large particles are formed via coagulation of smaller particles. Under the AC-agglomeration in the ESP (Laitenen et al, 1996), particles are firstly charged by a corona discharge. Next they enter an alternating electric field where they start to oscillate. The electrical mobility and also the oscillation velocity of particle depend on the particle size. Velocity and amplitude differences of the particles cause collisions between the fine and the large particles. If the particles remain attached to each other with unlimited contact time in ambient air, ultimately the particles increase in size. the fine particle numbers decrease and fine particles remain attached to the larger particles. Under the similar circumstances, the bipolar AC-agglomeration could occur

at the Thonburi air quality station. Then it seems that the fine particles, such as secondary particulate matter which cover the entire 10 nm to 1 μm size range (APEG, 1999) in the air around this station, agglomerate to larger particles and, then, they can survive through the mild heating in the BAM sampling system. Hence, a larger amount of the BAM-PM_{10} was always observed at this station. However, further research is required to confirm the assumptions and conclusion.

Finally it can be seen that the observed BAM-PM_{10} at Thonburi Electrcity air quality monitoring station is subjected to special conditions which are unusual compared to those at the other stations. So, the relationship between the BAM-PM_{10} and GHV-PM_{10} at this station should not take into an account on the estimated correction factor for assessing the GHV-PM_{10} at the roadside sites under normal condition. The correction factor for Thonburi Electrcity station as illustrated in Figure A1.2 is about 1.04.

A1.2 Influence of the Indonesian haze event on the regional background PM_{10} level in Thailand

Around September - October 1997, major forest fires occurred in Kalimantan and Sumatra, Indonesia, which led to the severe haze events in the Southeast Asia region and caused tremendous effects to many of the ASEAN nations. The Indonesian forest fires caused deterioration in the air quality of Southern Thailand in September 1997 (PCD, 2004). The daily average PM_{10} monitored at Hatyai, Phuket (an island in the Andaman Sea), and Suratani air quality stations located in Southern Thailand showed some changes during the episode. Daily PM_{10} were higher than the air quality standard (120 $\mu g/m^3$) on 24, 27, and 29 September at Phuket station and 25 September at Hatyai station. The daily PM_{10} observed at Suratani station during the event was below the standard because its location is in the upper part of Southern Thailand, whilst Hatyai and Phuket are located in the lower south. The annual and 5 percentile PM_{10} concentrations observed at Suratani are shown in Tables A1.1.

Table A1.1 PM_{10} in Suratani (unit: $\mu g/m^3$)

Year	Annual mean	5 percentile
1997	47.5	29.6
1998	32.6	13.8
1999	29.7	15.0
2000	31.7	16.0
2001	32.2	18.0
2002	53.9	38.0

The results in Table A1.1 seem to show that the haze event had a temporary influence on the annual mean and regional background PM_{10} in Suratani. After the event the PM_{10} level went down in the following year. Recently, slash and burn practices in Indonesia (Sumatra) have raised concern about another 1997 situation. This happened again in August 2002 (Vads Conner, 2003). This event gave some impacts on the PM_{10} levels in the southern part of Thailand as seen from the increase in both the annual mean and the 5 percentile PM_{10} concentrations.

Appendix 2

A2.1 Road transport emission in Bangkok

The Pollution Control Department updated the atmospheric emission inventory in the Bangkok Metropolitan Region (BMR) in 1997 and its projection in 2002 (PCD, 2000). The BMR, 7723 km^2 in total, covered six provinces of Bangkok, Samutprakarn, Nonthaburi, Phrathumthani, Nakornprathom, and Samutsakorn. This PCD's work provided the results of road transport emissions in the BMR in 1997 and 2002, as shown in Tables A2.1-A2.2. The 2002 projection also provided the road transport emissions in provinces as shown in Table A2.3. Table A2.3 was used to find backward to the percentage of road transport emission in Bangkok in 1997 as shown in Table A2.4. The percentage was applied to Tables A2.1 and A2.2 to obtain the road transport emissions in vehicle types in Bangkok in 1997 and 2002 as shown in Tables A2.4 and A2.5. The results indicate that the road transport emission of NO_x and PM_{10} in Bangkok was expected to decrease, but very slightly. The particles in the PCD emission inventory were total suspended particulate matter (TSP). It was found that the fraction of PM_{10} in TSP in Bangkok was around 0.6, as mentioned in Section 5.5 in Chapter 5. Thus a fraction of 0.6 was applied to obtain the PM_{10} emission density in the Bangkok Metropolitan Region (BMR).

Table A2.1 Road transport emissions by vehicle type in BMR in 1997 Unit: kt/y

Vehicle type	NO_x	SO_2	CO	HC	TSP
Petrol car	34.13	4.25	134.31	35.89	0.70
Light diesel vehicle	65.86	1.68	34.82	15.74	6.37
Large diesel vehicle	163.70	3.07	68.33	17.67	10.66
Motorcycle	0.98	0.79	112.31	163.68	2.87
Total	264.67	9.79	349.77	232.98	20.60

Source: PDC (2000b)

Table A2.2 Road transport emissions by vehicle type in BMR in 2002 Unit: kt/y

Vehicle type	NO_x	SO_2	CO	HC	TSP
Petrol car	40.06	4.99	157.64	42.12	0.82
Light diesel vehicle	62.27	1.77	32.94	14.89	6.02
Large diesel vehicle	144.01	2.70	60.11	15.54	9.38
Motorcycle	1.19	0.96	137.32	200.12	3.51
Total	247.53	10.42	388.01	272.67	19.73

Source: PDC (2000b)

Table A2.3 Road transport emissions by province in BMR in 2002 Unit: kt/y

Province	NO_x	SO_2	CO	HC	TSP
Bangkok	170.91	7.62	286.43	203.28	13.96
Samutprakarn	38.76	1.18	41.46	28.46	2.88
Nonthaburi	12.95	0.60	19.68	10.06	0.89
Phrathumthani	2.08	0.30	14.70	12.08	0.22
Samutsakorn	8.52	0.28	10.02	7.23	0.66
Nakornprathom	14.31	0.44	15.71	11.57	1.13
Total	247.53	10.42	388.00	272.67	19.74

Source: PDC (2000b)

Table A2.4 Fraction of road transport emissions by province in BMR in 2002

Province	NO_x	SO_2	CO	HC	TSP
Bangkok	0.69	0.73	0.74	0.75	0.71
Samutprakarn	0.16	0.11	0.11	0.10	0.15
Nonthaburi	0.05	0.06	0.05	0.04	0.04
Phrathumthani	0.01	0.03	0.04	0.04	0.01
Samutsakorn	0.03	0.03	0.03	0.03	0.03
Nakornprathom	0.06	0.04	0.04	0.04	0.06

Table A2.5 Road transport emissions by vehicle type in Bangkok in 1997 and 2002

Unit: kt/y

Vehicle type	NO_x	SO_2	CO	HC	TSP	PM_{10}
Year 1997						
Petrol car	23.55	3.11	99.12	26.74	0.49	0.30
Light diesel vehicle	45.44	1.23	25.70	11.73	4.50	2.70
Large diesel vehicle	112.95	2.25	50.43	13.16	7.54	4.52
Motorcycle	0.68	0.58	82.88	121.94	2.03	1.22
Total	182.62	7.17	258.13	173.57	14.56	8.74
Year 2002						
Petrol car	27.64	3.65	116.34	31.38	0.58	0.35
Light diesel vehicle	42.97	1.30	24.31	11.09	4.26	2.55
Large diesel vehicle	99.37	1.98	44.36	11.58	6.63	3.98
Motorcycle	0.82	0.70	101.34	149.09	2.48	1.49
Total	170.91	7.62	286.43	203.28	13.96	8.37