CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter consists of four parts of the results; the fist two sections provided the detail of the evaluation of the Air Pollution Model (TAPM) in prediction of meteorological parameters and air pollution parameters. The second part has been described the procedure in the development of Bangkok Vehicle Growth model (BVG) and Daily Traffic Localization model (DTL). Finally, the simulations of future Bangkok's air quality and proposed air management policy simulated by TAPM have been provided in the last two parts.

4.1 The Evaluation of The Air Pollution Model (TAPM) version 3.0

The aim of this evaluation is to explore the ability of TAPM to numerically simulate meteorological parameters and air pollutants in a densely populated, sub-tropical city. For meteorological simulation, the model has been employed to simulate surface temperature, wind speed and wind direction while model was run to simulate hourly level of carbon monoxide (CO) level in part of air pollution prediction.

For these simulations, TAPM was configured with four nested domains of 25×25×25 grids with grid spacing of 30, 10, 4 and 1 km for the meteorology, and 41×41 grids at 15, 5 and 1.5 km for the air pollution. The vertical grid has 25 levels from the surface to a height of 8 km. These simulations were run for the entire calendar year of 1999. The simulated meteorological results were then compared against observed data from meteorological sites at the Don Muang Airport (DMA) and the Sirikit Conventional Center (SRK) and air monitoring stations at Dindaeng (DIN) and Ladphrao (LAD). Two sets of TAPM simulations were made in which the local meteorological observations were and were not assimilated into the model runs.

The simulated CO concentrations were extracted from the nearest surface grid and have been compared with the hourly observations made at the Dindaeng (DIN), Ladphrao (LAD), Ramkhamhaeng (RAM), Ban Somdej (BAN) and Nontree Vidhaya School (NON) and Singharat (SING) sites as illustrated on Figure 4.1.

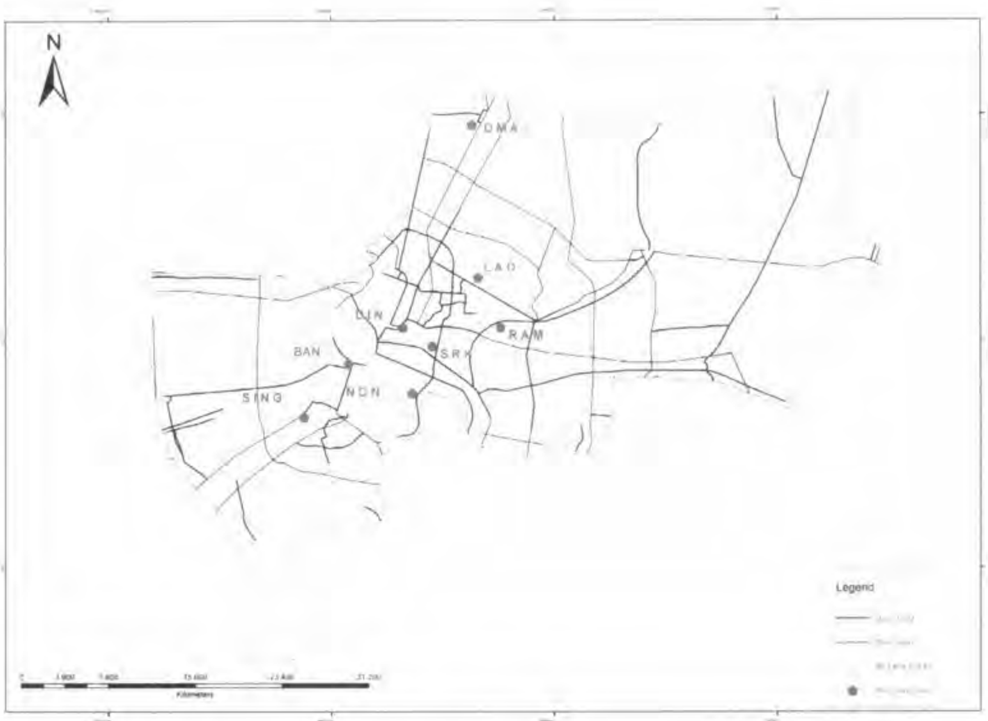


Figure 4.1: Location of air monitoring sites (DIN, LAD, RAM, BAN, SING and NON) and meteorological observation sites (DMA and SRK)

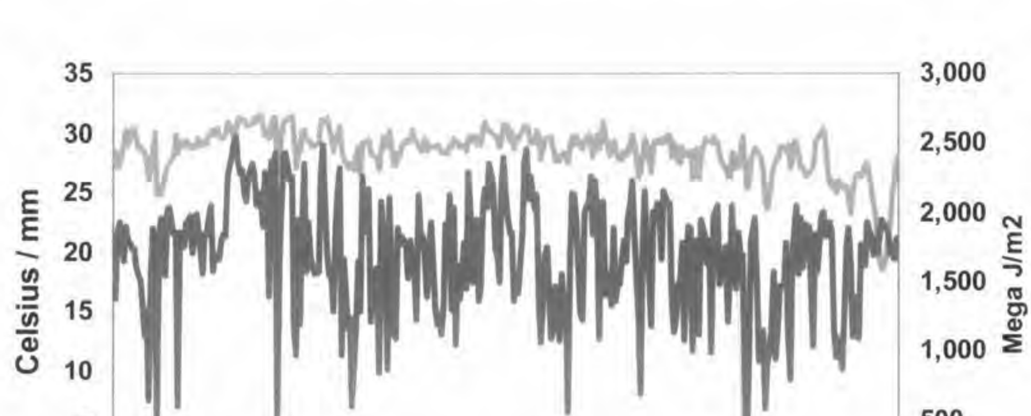


Figure 4.2: The daily mean of temperature, rainfall and radiation of Bangkok in 1999
Remark: data from SRK

4.1.1 Meteorological Simulation

a) Model Configuration

The simulation of meteorological variables, i.e., surface temperature, wind speed and wind direction have been conducted and compared against observation data at four location sites. The first 2 sites are roadside monitoring stations, namely Ladphrao (LAD) and Dindaeng (DIN) station, operated by Pollution Control Department (PCD) of Ministry of Natural Resources and Environment. The distance of these stations locate approximately 5 m from curbside where wind speed and wind direction are measured at 10 m height and temperature at 3 m height. The another 2 sites are official meteorological observation station, namely Don Muang International Airport (DMA) and Sirikit National Convention Center (SRK), operated by Thai Meteorological Department of Ministry of Information and Communication Technology where these 2 sites provide hourly surface temperature, wind speed and wind direction collecting at 11 m height. The TAPM observations are for the inner-most grid (500 m spacing) that contains these individual states. Model results are extracted at the lowest model level in TAPM (10 m) at each of these sites. The table 4.1 below shows the configuration in this simulation

Table 4.1: The configuration of TAPM for meteorological simulation

TAPM Parameters	Simulation setting
Number of grid point	25x25x25
Number of grid domain	4 domains
Resolution of grid domain	30, 10, 3 and 1 km.

b) Statistical Analysis

The statistics used in this evaluation based on numerous paper (i.e., Willmott (1981) and Pielke (1984)) that have been applied these following statistical indexes for model evaluation. The indexes using in this evaluation are arithmetic mean of data (MEAN), standard deviation (STD), the Pearson correlation coefficient (CORR) as well as the standard Root Mean Square Error (RMSE) and the Index of Agreement (IOA). The statistic formulas have been expressed as bellowed; whereas N is number of data, O_i is observed data, P_i is prediction data and O_{mean} is average value of observed data.

- Pearson Correlation Coefficient (CORR)

$$\text{CORR} = \frac{N\left(\sum_{i=1}^{N} O_i P_i\right) - \left(\sum_{i=1}^{N} O_i\right)\left(\sum_{i=1}^{N} P_i\right)}{\sqrt{\left[N\left(\sum_{i=1}^{N} O_i^2\right) - \left(\sum_{i=1}^{N} O_i\right)^2\right]\left[N\left(\sum_{i=1}^{N} P_i^2\right) - \left(\sum_{i=1}^{N} P_i\right)^2\right]}}$$

- Root Mean Square Error (RMSE)

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (P_i - O_i)^2}$$

- Index of Agreement (IOA)

$$\text{IOA} = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left(|P_i - O_{\text{mean}}| + |O_i - O_{\text{mean}}|\right)^2}$$

c) Bangkok Meteorological Condition

The data from Thai Meteorological Department in year 1999 has been analyzed with aiming to capture meteorological condition governing in Bangkok airshed. The targeted data covering daily mean of surface temperature, rainfall and radiation are illustrated in figure 4.2. The daily temperature (pink line) and radiation (red line) reached the highest level in March and April. By nature of summer season, daily temperature was higher above 30^0 C and daily radiation was above 2,000 Mega J/m^2. Although there were some precipitation in April and May but rainy season has totally begun in July, and then, the raining finished in October. During September – October, the daily rainfall was measured as 4.1 mm. For winter, the beginning of season was in the middle of November, the daily temperature was measured below 27^0 C while lowest mean temperature detected at 18.9^0 celsius at late of the year.

d) Simulation Results

The results of meteorological simulation against observation data has been shown in table 4.2, the discussion of simulated surface temperature, wind speed and wind direction are also described in the next following;

(1) Surface temperature

The observed and predicted surface temperatures were compared in table 4.2a. The results indicated the under-prediction of simulated temperature at annual average value compared to observed data. The difference of data between the observed and modeled values was range from 1.7^0 - 2.1^0 C among four monitoring sites. The RMSE was found between 3.01-3.15 while CORR and IOA were derived in range of 0.4-0.8 and 0.74-0.8, respectively. From the result, although the RMSE score is high but IOA score was found in within acceptable range (>0.6) and the highest CORR and IOA were found at the DMA and SRK. The model underestimation could be effected by the urban heat island (UHI). While the surface processes represented within TAPM have been set for an urban area, it does not appear that they have been fully adjusted for the tropical environment. Hung et al. (2005) has found that Bangkok suffers from a significant UHI effect with overnight temperatures often increase 6.0^0 C in the heart of the metropolitan area higher than the surrounding suburban. This is similar to many of the mega-cities in Asia. Boonjawat et al. (2000) also reported an increase in temperature 5.5^0 C overnight in comparison to the outlying areas. These results are consistent with the observed discrepancy being largest at the LAD and DIN which are in the most densely populated region.

Table 4.2 : Meteorological simulation results

SITE NAME	NUM_OBS	MEAN_OBS	MEAN_MOD	STD_OBS	STD_MOD	CORR	RMSE	IOA
a) Surface Temperature (Celsius)								
DIN	7076	29.1	27.4	2.9	4.0	0.8	3.10	0.74
LAD	8377	29.3	27.5	3.1	4.1	0.4	3.15	0.80
SRK	8755	28.4	26.3	3.1	3.9	0.8	3.10	0.82
DMA	8760	27.6	25.9	3.4	4.2	0.8	3.01	0.84
b) Wind Speed (m/s)								
DIN	7019	0.8	2.3	0.4	0.8	0.9	1.72	0.30
LAD	8406	0.7	2.7	0.4	1.1	0.3	2.21	0.11
SRK	4926	1.9	2.7	1.0	1.0	0.2	1.49	0.48
DMA	8525	3.3	3.0	1.9	1.3	0.4	1.96	0.55

Remark: OBS: observation; MOD: model predictions; MEAN: arithmetic mean; STD: standard deviation; CORR: Pearson correlation coefficient (0=no correlation, 1=exact correlation); RMSE: root mean square error (0=good); IOA: index of agreement (0=no agreement, 1=exact agreement)

(2) Wind Speed

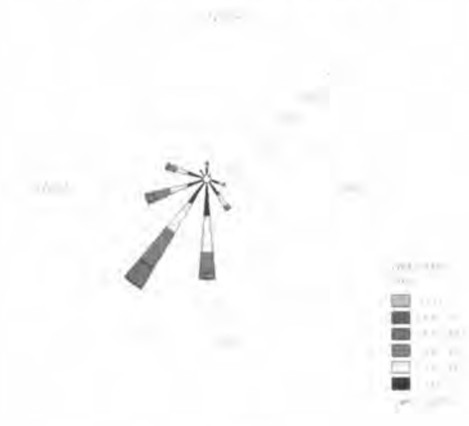
From table 4.2b, the average year-long of observed and modeled wind speeds have been provided while TAPM used synoptic wind data for wind speed simulation but measured wind speed has been detected on hourly basis by wind detection equipment at 10 meters height for DIN and LAD and 11 meters height for DMA and SRK. The result indicated that the modeled wind speeds from TAPM were potentially overestimated at all sites comparing to observed wind data from the DIN and LAD that showing weaker wind speeds (less than 1.0 m/s). Among these four sites, the RMSE score was ranged between 1.49-2.21, CORR derived from 0.2-0.9 and IOA was found in range of 0.11-0.55. It can be noticed that the DMA and SRK, located in suburban and low-rise building area, had stronger measured wind speed and showing better RMSE and IOA score than DIN and LAD which located in urban area and surrounded with higher building. This could confirmed the important of geographical effect (high-rise building effect) that potentially played significant role on strength of measured wind speed particularly for monitoring site locating in urban area. This effect could explain the weaker of measured wind speed and low RMSE and IOA score at DIN and LAD at which TAPM didn't take this effect into account.

(3) Wind Direction

Due to sensitivity of measured wind direction which easily disturbed by building effect nearby, the evaluation was made on combination of measured data from SRK and DMA (the distance between two sites are approximately 20 km and still representing the same urban air-shed of Bangkok) which having less building effect and locating in suburban and low-rise building area. As shown in figure 4.3, given the strong seasonal cycle of the wind direction in Bangkok, the analysis focuses on the two well-defined seasons. For the period of Southwesterly wind, known as wet season, during May-October (shown in figure 4.3a and 4.3b) the model has performed well in prediction wind direction for this period. The model has over predicted the frequency of weak wind speeds while under predicting the higher wind speeds (5.7-8.8 m/s, blue color). However, TAPM calculations showed good agreement in the prediction of calm conditions. During the Northeasterly wind (or commonly known as dry season) as shown in figure 4.3c and 4.3d, the model over predicts the occurrence of weak winds (2.1-3.6 ms^{-1}) at the expense of calm conditions. Overall, the simulations of the wind direction did not score well in comparison to the observations during the dry season.

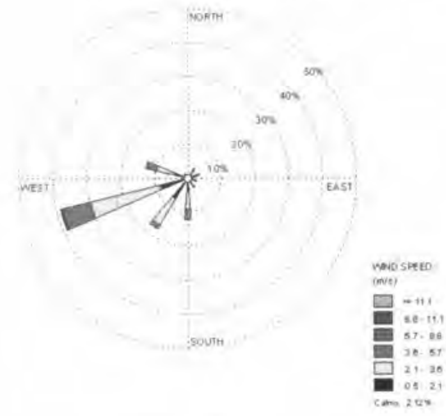
Because TAPM integrated data from synoptic wind information to simulate pattern of wind field (movement of wind or wind direction) at ground surface level which probably not able to capture disturbance of local wind movement that normally influencing the direction of observed wind data. From the observed data during dry season in figure 4.3c, it's could be noticed that there were great variation of wind direction in observed data that confirmed local wind disturbance during transitional period before beginning of winter. This could explain why TAPM performed well on the major local wind (Southeasterly and Northwesterly wind), however, model showed error in representing some local wind that having great disturbance particularly in seasonal transition period.

Observation (Wet Season)



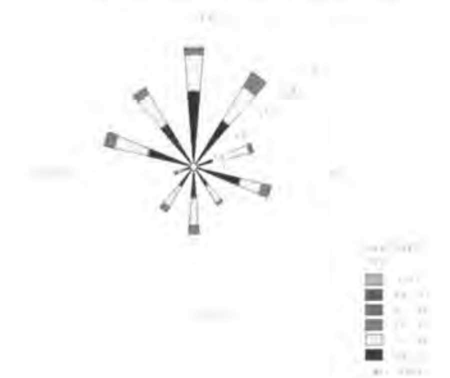
(4.3a)

Model (Wet Season)



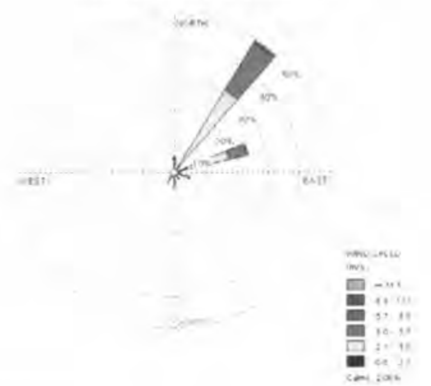
(4.3b)

Observation (Dry Season)



(4.3c)

Model (Dry Season)



(4.3d)

Figure 4.3: The combined data of observed and modeled wind direction at SRK and DMA during 1999, (4.3a): Observed wind direction during effective Southwesterly wind period or wet season (May-October, 1999); (4.3b): Modeled wind direction during effective Southwesterly wind period or wet season (May-October, 1999); (4.3c): Observed wind direction during effective Northeasterly wind period or dry season (January, February and December, 1999); (4.3d): Modeled wind direction during effective Northeasterly wind period or dry season (January, February and December, 1999)

4.1.2 Air Pollution Simulation

In these simulations, TAPM was configured in tracer mode for CO, with three nested domains of 25×25 grids with grid spacing of 30, 10 and 3 km for the meteorology, and 41×41 grids at 15, 5 and 1.5 km for the air pollution. The vertical grid has 25 levels from the surface to a height of 8 km with 13 levels in the lowest km. The date of simulations was covered the entire calendar year of 1999. The simulated CO results were then compared against monitored CO at Dindaeng (DIN), Ladphrao (LAD), Ramkhamhaeng (RAM), Ban Somdej (BAN) and Nontree Vidhaya School (NON) station. Two sets of TAPM configurations were tested in which the local meteorological observations were assimilated (TAPM#) and local meteorological were not assimilated (TAPM) into the model runs

a) Model Configuration

The Air Pollution Model (TAPM) version 3.0 was configured to predict CO concentration at Dindaeng and Ladphrao road. TAPM was set up at resolution of 25x25x25 grid number and grid spacing of 30, 10, 4, 1 and 0.5 km for air pollution grid domain.. Two options of using meteorological assimilation had been selected (with and without meteorological assimilation). As for option of meteorological assimilation, the hourly wind direction and wind speed at SRK observation station has been employed as well as Eulerian mode has been selected to simulate hourly CO. The overall configuration was concluded and showed in table 4.3

Table 4.3: The configuration of TAPM for air pollution simulation

TAPM Parameters	Simulation setting
Number of grid point	25x25x25
Number of grid domain	4 domains
Resolution of grid domain	30, 10, 3 and 1 km.
Meteorological option	2 setting: with and without assimilated data
Air pollution option	Eulerian mode

b) Statistical analysis

For this analysis, the statistical indexes used for evaluation of CO prediction are Root Mean Square Error (RMSE), Index of Agreement (IOA), annual average (AVG) and percentile of data (90^{th}, 95^{th}, 99^{th} and 99.9^{th}) following model validation conducted by Willmott, 1981. These tests were applied for an entire year in an effort to validate the performance of the TAPM simulations. Similar analysis was undertaken for the CO concentrations. In addition, the Robust Highest Concentration (RHC) (Hurley et al., 2003 and Hannah, 1998), which commonly used in model evaluation studies, was used to evaluate the prediction of extreme (high) concentrations by the model. As formula defined below, $C(R)$ is the R^{th} highest concentration and $\bar{C}$ is the mean of the top R-1 concentrations. A value of $R = 11$ is used here so that $\bar{C}$ is the average of the top 10 concentrations

$$\mathrm{RHC} = C(R) + (\bar{C} - C(R))\ln\left(\frac{3R-1}{2}\right).$$

c) Emission Inventory

The accuracy of these simulations depends not only on the ability of TAPM to accurately simulate the meteorology of Bangkok, but also on an accurate emissions inventory of the region. For this research, the CO inventory using here was developed by the PCD during 1997-1998 consists of point, area and line sources and covers the entire Bangkok Metropolitan Region (BMR), which includes other nearby provinces. The amount of CO emitted according to the various source contributions is shown on table 4.4

Table 4.4: The CO emission inventory (ton/year) for Bangkok and vicinity province

Sources	**Bangkok**	**Vicinity Provinces**[1]
Area	909	103,271
Mobile	249,320	100,451
Point	4,467	5,356
Sub Total	254,696	209,078
Total BMR	463,774	

Source: PCD (2000a), Remark: [1]Samutprakarn, Samutsakorn, Nontaburi and Pratumthani

Table 4.5: BMR emission inventory categorized by type

Type	Sources	Procedure
Point	Factory Crematory Incinerator	Field-survey Questionnaire Emission Factor
Line	large-diesel Small-diesel Gasoline Motorcycle	Vehicle Lab test Emission Factor Mobile5 model
Area	Household Petrol Station Airport Waste Landfill	Emission Factor Population density Fuel consumption

The emission inventory was designed to capture all significant sources of CO; the data were collected and surveyed during 1997-1998. Over 7,000 industrial factories that use fuel for heat generation, including 1,204 crematories and incinerators, were grouped as point sources. Inventories for sulfur dioxide, nitrogen oxide and particulate matter were also determined as part of this project.

Traffic data was collected along 63 major routes across Bangkok. Traffic counts were made by video recorder and classified into 50 road types following the designation of road network configured in the PCD's system. Ultimately, the CO emissions were derived based on a formula defined by using four vehicle types; large-diesel engine, small-diesel engine, gasoline engine and motorcycle; all sampling vehicle types were tested by constant volume sampling (CVS) at the PCD laboratory. The combination of emission factors was calculated from the air emission model, Mobile5 (PCD, 2000b). Traffic field data (type, number, hourly ratio and velocity) have been used to calculate the emissions generated for the specified roadways.

The CO emissions from households, airports and waste management landfills were grouped as part of the area-typed sources. The entire Bangkok Metropolitan Region (BMR) was broken down into 500 x 500 m^2 grid; emission rates were calculated from fuel consumption per capita and the population density. The airport emissions were estimated from the type and number of flights recorded. Likewise, waste management emissions were also measured as an area source. Finally, for petrol stations, the fuel sales rate was recorded and used to compute an area emission rate. The summary of the emission inventory development is shown in table 4.5.

In this study, the completed CO emission inventory data in the year 1997-1998 have been used, as the inventory data in 1999 were not well developed. The ambient CO hourly data and meteorological data were complied for 1999. The inherent error in using 1997-1998 emissions inventories against 1999 CO observations is relatively small given the means from which the inventories were calculated.

d) Background concentrations

The CO emission inventory data represent all local sources of carbon monoxide, but exclude other regional sources that contribute to the background concentration coming into the airshed. Therefore, we need to estimate the background concentration of CO due to these regional sources and due to the natural CO concentration as well. There are various approaches to estimate the air pollution background levels in the urban environment. For example, Cooper (1987) estimated background CO levels from the impact of indirect sources on observed CO concentrations and air quality. Both Liu and Jeng (1993) and Ireson (1993) used a meteorological dispersion model to estimate background concentrations of CO. However, there is no final agreement on the best procedure providing accuracy enough to measure this concentration. Perhaps the most common practice suggested by regulatory agencies is that the CO background can be determined from existing monitoring sites where the monitoring location is not significantly affected by nearby roadways or intersections (US EPA, 1992).

For the simulations presented here, the background CO concentration was defined by the observations taken from hourly CO data during 1999 at the Singharat (SING) monitoring station. This site is located away from dominated traffic routes on the outskirts of the urban area and was defined by PCD for representing general area in Bangkok airshed. The annual averages of CO concentrations at the hour of lowest traffic volume during 02:00- 04:00 am have been analyzed and showed in figure 4.4

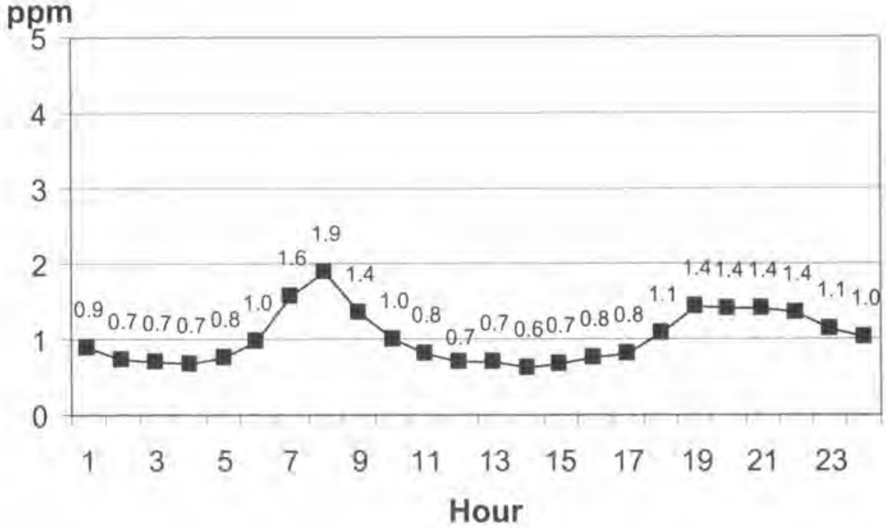


Figure 4.4: The hourly annual average of CO concentration at SING in 1999

From figure 4.4, the year-long average of hourly CO concentration showed obviously peak at morning time and evening time. The CO peak was reached highest peak at 08.00 am and during 19.00-22.00 pm at level of 1.9 ppm and 1.4 ppm, respectively. During early morning of the day (01.00-06.00 am), CO level derived from 0.7-0.9 ppm, and then after the rush hour peak, the CO has been dramatically decreased between 0.6-0.8 ppm. In order to determine the CO background using for TAPM simulation, the period after midnight which commonly found as lowest amount of traffic (or during 02.00-04.00 am) has been targeted to extract the CO background level. From statistical calculation, the average CO concentration (AVG) during 02.00-04.00 was 0.7 ppm as well as the standard deviation (STD) was 0.79. Thus, the level of CO at 0.7 ppm has been input as CO background for simulation. However, because the STD was slightly greater than AVG value, so the uncertainty needs to be aware while interpreting the model results.

e) **Simulation Results**

(1) Year-long simulation

The year-long simulated CO comparing against monitored CO from 6 urban monitoring sites has been shown in figure 4.5. Both sets of simulations are found to slightly over predict the CO concentration at all sites with the SING site showing the least amount of error. This is not surprising since we extracted the CO urban background from this location. The model performed very well in the annual average value (AVG) when compared to the field observations but revealed an over estimation of the RHC and MAX. The observed CO concentration is found within a range of 0.6 - 3.0 ppm where the maximum CO concentration was found at the DIN site and the minimum was found at the BAN site. The simulated CO concentrations (TAPM) varied from 1.2 - 2.5 ppm with the maximum concentration (2.5 ppm) found at the NON site and the minimum concentration (1.2 ppm) found at the SING site. The simulated CO concentrations from the TAPM# runs (with meteorological assimilation) are ranged between 1.6-3.7 ppm with the minimum at SING and the maximum found at NON.

Although the comparison between TAPM simulations and observations is essential, there is another need to evaluate the model to represent the movement of air pollution covering the entire urban air-shed area of Bangkok. Therefore, the comparison of observation and model where the data combined from all six sites (unmatched-in-time) has been analyzed and the data illustrated in figure 4.6. The TAPM performed good accuracy at AVG, 90^{th} and 95^{th} percentile of data as well as TAPM# also showed good performance at AVG of data.

Breaking the time period up to cover the two dominated monsoon conditions (wet and dry season), figure 4.7 has illustrated the hourly CO concentration during the middle of the winter (or dry season) during January-February and the high humidity period in the wet season (August-September). This analysis only considers the TAPM# model configuration. Simulated concentrations are compared to the DIN observations. As the DIN site is located in the center of Bangkok, it represents the urban area of Bangkok. The results for the dry season indicate a good agreement. Unlike the dry season, the TAPM# simulations for the wet season showed considerably more variability and a lower overall skill score.

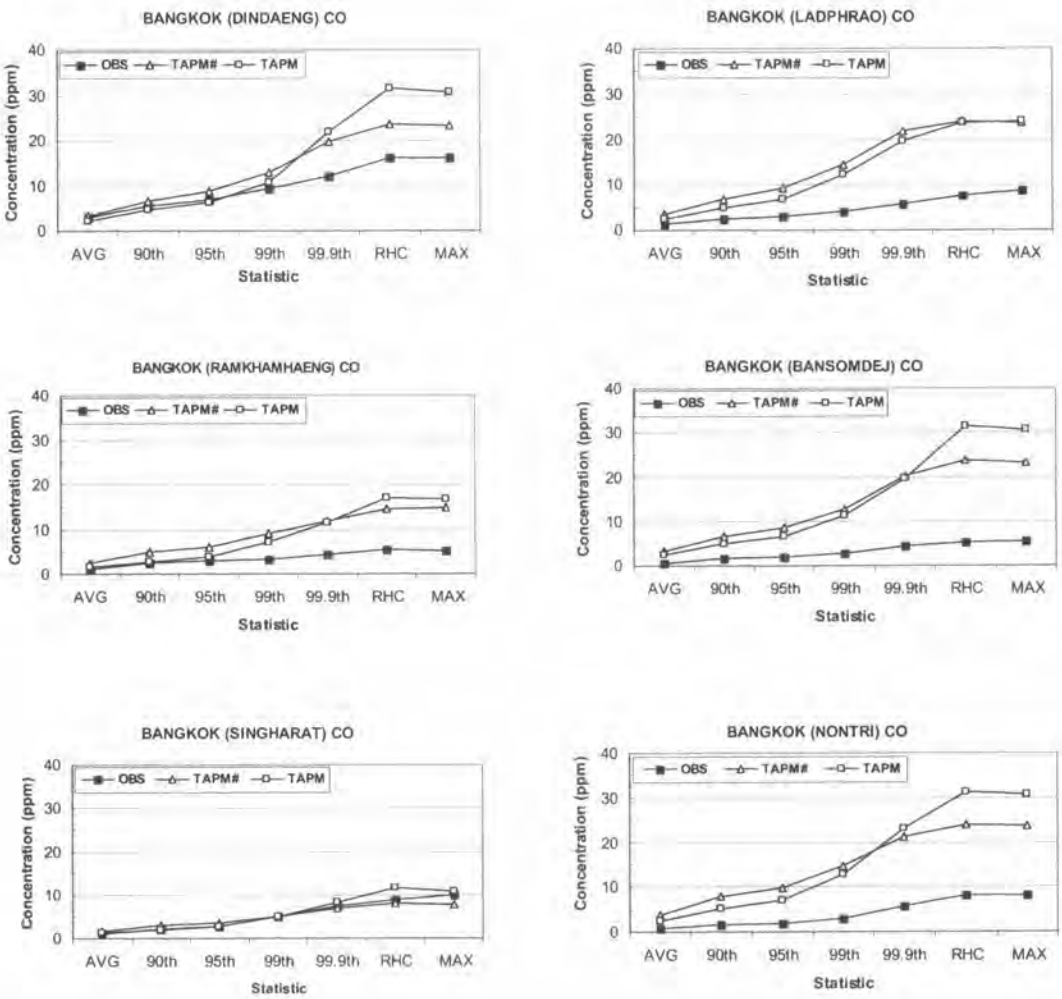


Figure 4.5: Comparison of CO from 6 sites in Bangkok between observation data (OBS) against model with meteorological assimilation (TAPM#) and model without meteorological assimilations (TAPM)

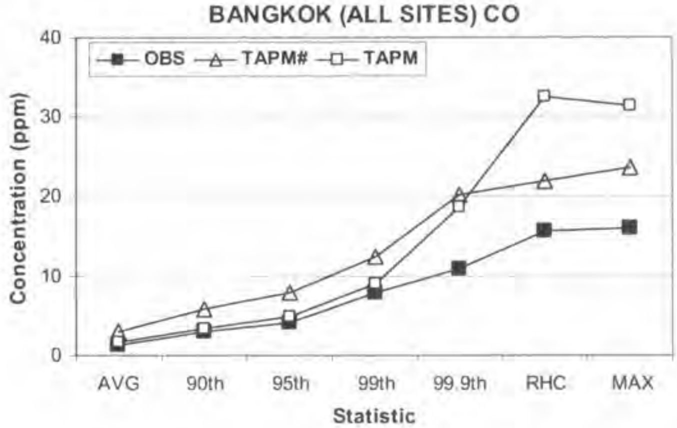


Figure 4.6: Comparison of CO combined from 6 sites between the observation data (OBS) against model with meteorological assimilation (TAPM#) and model without meteorological assimilation (TAPM)

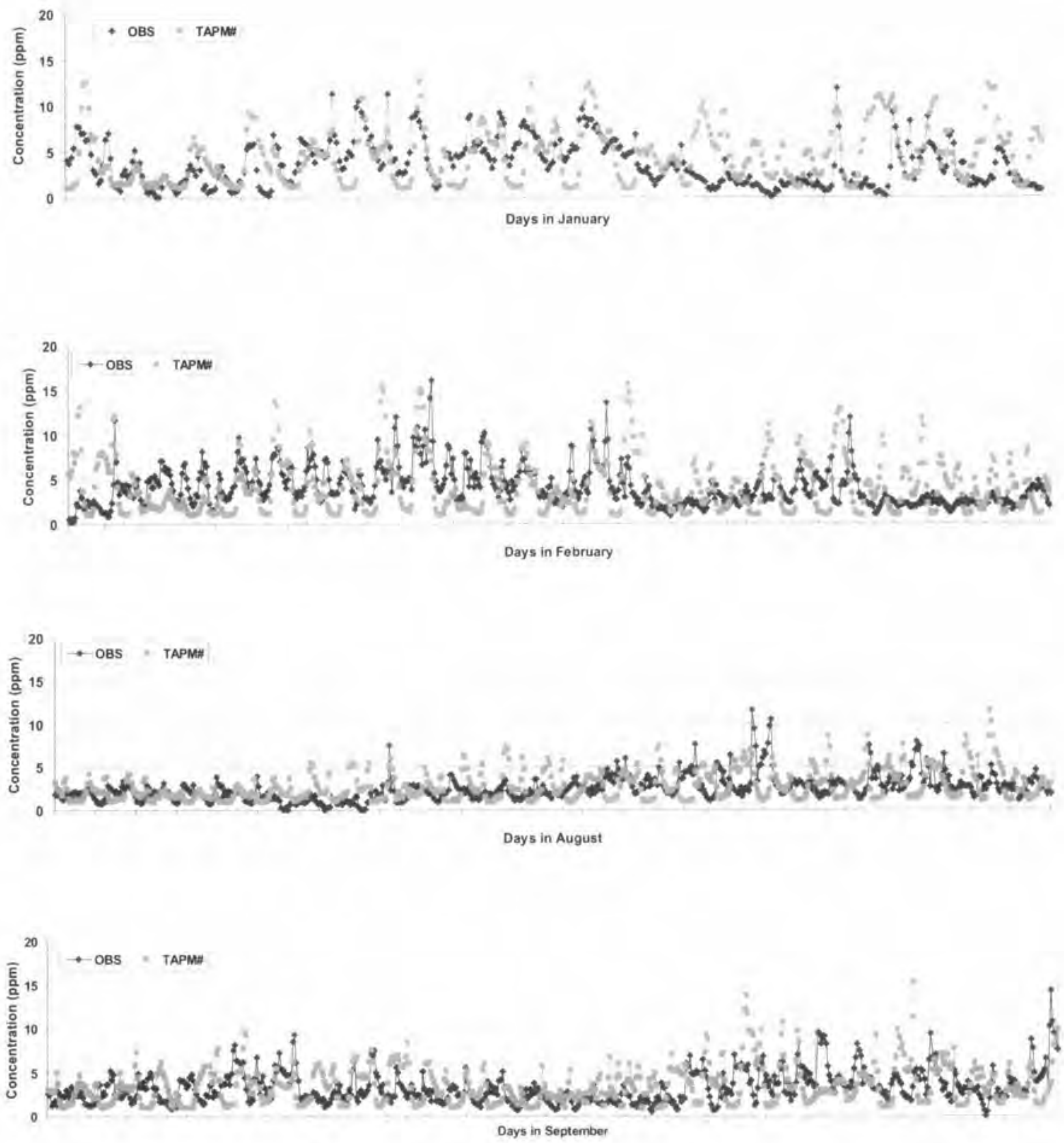


Figure 4.7: Hourly CO concentration between model and observation in dry season (January and February) and wet season (August and September) at DIN in 1999

(2) Case Study

In order to simulate case study running, The Air Pollution Model (TAPM) version 3.0 has been configured to predict hourly CO concentration comparing against monitored CO at Dindaeng roadside monitoring station. TAPM was set up at resolution of 25x25x25 grid number and grid spacing of 30, 10, 4, 1 and 0.5 km for air pollution grid domain.. Two options of using meteorological assimilation had been selected (with and without meteorological assimilation). As for option of meteorological assimilation, the hourly wind direction and wind speed at SRK observation station has been employed as well as Eulerian mode has been selected to simulate hourly CO. The overall configuration was concluded and showed in table 4.6

Table 4.6: The configuration of TAPM for case study simulation

TAPM Parameters	Simulation setting
Number of grid point	25x25x25
Number of grid domain	4 domains
Resolution of grid domain	30, 10, 3 and 1 km.
Meteorological option	2 setting: with and without assimilated data
Air pollution option	Eulerian mode

For the result of three case studies (showed figure 4.8), one sees that for winter both TAPM# and TAPM show good agreement with the observed CO concentrations. The observed concentration of CO ranged from 1.2 - 12 ppm, while TAPM# and TAPM concentrations ranged from 0.2-14.9 ppm and 0.7-14.5 ppm, respectively. In case of transition period, strong correlations with the observations could be seen for both the TAPM# and TAPM configurations. It is further noted that the peak concentrations of TAPM# are generally stronger than those of the TAPM through out the period of simulation.

However, the rainy simulation by TAPM# and TAPM, greatly over estimated the CO concentrations and show little skill with the observations. The simulated peak concentrations ranged between 12 – 23 ppm while the observed peaks were ranged between 0.8 – 9.6 ppm. Moreover, the timing of these peaks does not match between simulations and observations. This error is consistent with our understanding of TAPM's inability to dynamical simulate deep convection.

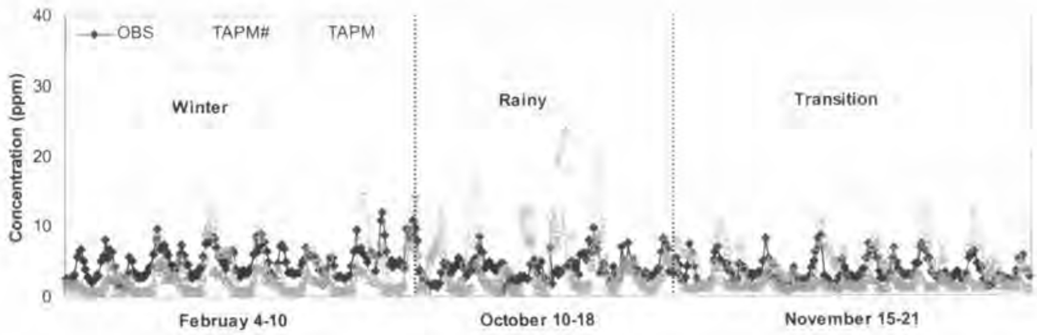


Figure 4.8: Spatial variation of simulated CO from model with meteorological assimilation (TAPM#) and model without meteorological assimilation (TAPM) against monitored CO at DIN during three simulation periods

Table 4.7: The statistic evaluation of TAPM with and without meteorological against monitoring data at DIN (unit representing in ppm)

Index	Winter		Rainy		Transition		Year-long	
	TAPM#	*TAPM*	*TAPM#*	*TAPM*	*TAPM#*	*TAPM*	*TAPM#*	*TAPM*
MEAN_OBS	5.08		4.01		3.50		3.01	
MEAN_MOD	3.30	2.24	4.65	4.34	4.05	1.62	3.34	2.38
STD_OBS	2.14		1.71		1.69		1.90	
STD_MOD	3.50	1.80	4.11	5.16	2.77	0.68	2.65	2.19
RMSE	3.13	3.42	4.21	5.38	1.97	2.15	2.68	2.91
IOA	0.7	0.56	0.38	0.21	0.79	0.26	0.58	0.37

Remark: TAPM#: model with meteorological assimilation; TAPM: model without meteorological assimilation; OBS: observed data; MOD: modeled data; MEAN: arithmetic mean; STD: standard deviation; RMSE: root mean square error (0=perfectly accurate); IOA: index of agreement (0=no agreement, 1=exact agreement)

The statistical evaluations, indicated by arithmetic mean (MEAN), standard deviation (STD), root mean square error (RMSE) and index of agreement (IOA) are summarized in table 4.7. For three cases of simulation, the observed CO at DIN was measured at range of 3.50 - 5.08 ppm from transition to winter and 3.01 ppm for year-long simulation while modeled CO by TAPM# and TAPM derived from 3.30 – 4.65 ppm and 1.62 – 4.34 ppm, respectively. From the result indicated best score of model simulation during transition period and followed by the winter case. The score of RMSE for TAPM# derived from 1.97 - 4.21 from transition to rainy as well as the TAPM was in range of 2.15 - 5.38 from transition to rainy. Due to considerably good IOA score (IOA>0.6) of TAPM# at transition and winter period, these also indicated the better simulation result for model running with meteorological assimilation (TAPM#). The RMSE and IOA of the year-long simulations are also presented. The mean of modeled CO was in range of 2.38 for TAPM and 3.34 for TAPM# while observed data was 3.01. Considering RMSE and STD score at year-long simulation, the result revealed the justified performance of TAPM with both two options in simulating for year-long data while RMSE score was greater than STD score (or RMSE>STD). These scores also confirmed the better performance of model with meteorological option (TAPM#) while model without meteorological option (TAPM) are considerably accepted.

4.1.3 Discussion and Concluding Remark

Meteorological Simulation

As for meteorological prediction, the under-prediction of surface temperature comparing to the observe could be explained by the effect the Urban Heat Island (UHI) that causing year-long average of measured temperature greater than the simulation. By the works of Hung et al. (2005) and Boonjawat et al. (2000) have been confirmed the significant evidences of UHI in Bankok same as other Asian cities, at which the temperature of inner Bangkok is higher about 6^0 C compare to the outskirt suburban area. These effects seem to not be completely adjusted for tropical environment like Bangkok.

The effect of urban geography (high-rise building effect) that potentially played significant role on strength of measured wind speed (very low wind speed in monitoring data) especially for urban monitoring site, however, but model likely not take enough account on this circumstances. This effect could appropriately explain the over-prediction of simulated wind speed while TAPM simulating the wind speed on the assumption of no effect of high-rise building (urban geography). In other hand, measured wind speed at LAD and DIN, which both located in the heart of Bangkok, got interference from urban building bloc and leading to very weak monitored wind speed data

Although model was well captured Southwesterly wind in wet season but not performed well in prediction of Northeasterly wind during dry season (or winter), the observed data showed that the wind have blown from various directions while TAPM simulated dominantly from Northeast direction. Because TAPM simulates movement of wind pattern (or wind direction) by integration process from synoptic data at above boundary layer. This integrating process probably not able to capture disturbance of local wind movement that normally influencing the direction in observed wind data.

Confirm by observed data, there were great variations of wind direction that commonly occurred during transitional period (before beginning of winter). This could explain why TAPM can not performed well on some period that having great disturbance particularly in seasonal transition period.

Air Pollution Simulation

For air pollution prediction, the simulated CO was compared to 6 monitoring sites in Bangkok. The year-long simulated results showed good agreement with monitoring data at AVG, 90^{th} and 95^{th} percentile of data while TAPM without meteorological data assimilation (TAPM) shows least amount of error. With breaking into 2 well-defined season (wet and dry), TAPM was predicted at good correlation during dry season (January and February). However, in contrast, TAPM showed poor correlation in wet season (August and September).

There were several reasons to explain why the TAPM simulations had performed relatively poor during the wet. In fact, the accuracy of simulation result strongly depending on the quality of input data, which mean that the quality of emission inventory in representing the accurate amount of traffic emission need to be investigated. Based on procedure in developing emission inventory, PCD had given full attempt to cover all potential air pollution sources on the basis of 'best available practice'. From experience of Mensink (2004) conducted the emission inventory validation works, from the result indicated that even the most reliable emission factor (derived from COPERT II); the results also revealed the large uncertainty specially from traffic source due to condition of vehicle maintenance and driving behavior. In the same way, there is limited number of validation works to confirm the accuracy that has been constructed by PCD and applied in this work.

The wash-out process in diluting air pollution in urban atmospheric is another sources of over-estimation in TAPM simulation. Even though model has been configured to calculate hourly rainfall (setting to rain-on process) but from figure 4.9 indicated that model was under-predicted in simulation of hourly rainfall during rainy case study (October 10-18, 1999). As a result of under-predicted rainfall generated by TAPM, therefore, the dilution of CO from atmosphere by wash-out process could not taking effect, and then causing the overestimation of modeled CO for case study and year-long simulation.

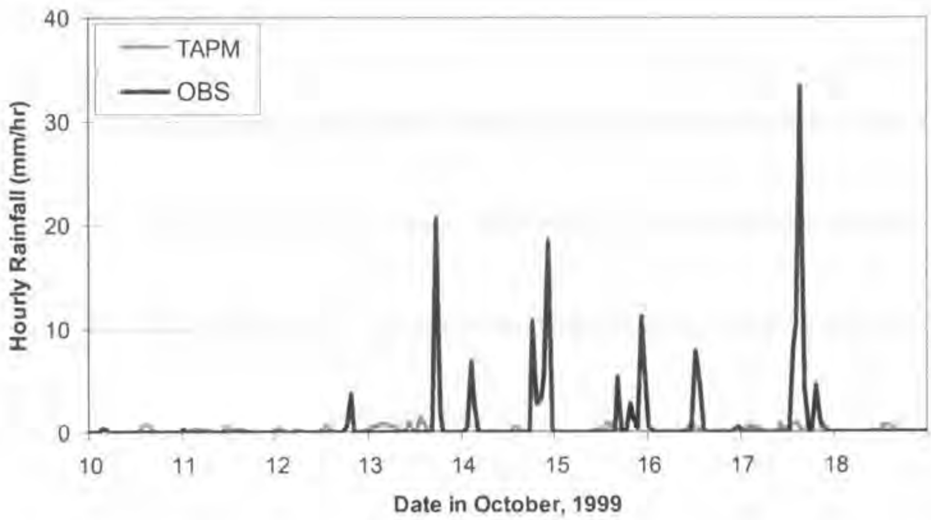


Figure 4.9: The hourly rainfall of model and observation during rainy period (October 10-18, 1999), Remark: Observed data obtained from SRK station

In particular, it is likely that TAPM is incapable of simulating deep convection that dominated the region over those months. TAPM has primarily been designed to accurately simulate the boundary layer air pollution while being computationally efficient. It has not been designed to consider deep convection through the free troposphere due to the computation expense. In particular, TAPM maintains an upper boundary of 8 km, which is inappropriate over Thailand during the rainy monsoon. This deep convection will lead to a large removal of carbon monoxide from the boundary layer. As this ventilation is not physically possible in TAPM, one would speculate that during the summer months TAPM would over estimate the CO concentrations. This is not guaranteed, however, since the entire boundary layer dynamics will no longer be physically realistic.

During the winter monsoon, especially during events of cold air outbreak, it would be expected that TAPM would be much more accurate, as it found in these simulations. During periods in which deep convection is not prevalent, TAPM should be quite skilled in simulating the boundary layer dynamics and hence the CO concentrations.

The National Ambient Air Quality Standard (NAAQS) for one hour of CO is 30 ppm and for average 8 hours of CO is 9 ppm. Although most of the CO observations in this study were not in excess of the hourly standard level, the long term 8 hours values were higher than the standard at some sites. Given that the primary source of CO emissions in Bangkok is from vehicle emissions, which is common in many Asian cities, urban planners should be aware of the effect of increasing the number of new vehicle registrations will have on CO concentrations.

4.2 The Development of Bangkok Traffic Scenario

This section provides detail on simulation of future traffic scenario that has been formulated base on statistical data. To develop future traffic scenario, the development of Bangkok Vehicle Growth model (BVG) and Daily Traffic Localization model (DTL) have been developed in order to predict annual vehicle growth in Bangkok and daily traffic volume that would occupy on DIN and LAD road in future year.

4.2.1 The Bangkok Vehicle Growth (BVG) model

Among various theories on vehicle ownership models, based on readiness of available data required in theoretical analysis and objective suitability for this research, quasi-logistic function is chosen in order to estimate annual vehicle growth in Bangkok. Buttun et al. (1993) suggested that quasi-logistic function is not only easily to calibrate but flexible and directly interpret. The approval of satisfactory of this model had been approved to used in developing country like Thailand (household model by Cundill (1986) and aggregate model by Buttun et al. (1993)) The quasi-logistic function can be written in equation 4.2 as following;

$$C_t = \frac{S}{1 + e^{-a} X_1^{-b_1} X_2^{-b_2} \ldots\ldots X_n^{-b_n}} \qquad \text{(eq. 4.1)}$$

Where;

C_t is the vehicle ownership per population.

S is the saturation level of vehicle ownership per population

X_n are explanatory variables

a, b_n parameters to be estimated

a) Analysis of Explanatory Variables

According to the model, the explanatory variables have to be investigated in order to calculate vehicle ownership (C_t). For this research, there is a need to specified explanatory variable that showing relationship with the growth of vehicle registered in Bangkok. Therefore, the annual new vehicle registration number has been selected to be independent variable and any relevant variables have been screened by correlation analysis method. Based on history of 15-year data record since 1989, vehicle data and economic data have been analyzed for correlation analysis related to annual new vehicle registration number. The table 4.8 provides the detail of screening data for determination of explanatory variables as well as table 4.9 shows the results of this method

Table 4.8: Detail of screening data for construction of Bangkok Vehicle Growth (BVG) model

Statistical Index	▪ Correlation Analysis $Corr(X,Y) = \frac{\Sigma(X-\bar{X})(Y-\bar{Y})}{\sqrt{\Sigma(X-\bar{X})^2 \; \Sigma(Y-\bar{Y})^2}}$
Data Range	▪ Since 1989 to 2005[\1]
Independent Variable[\2]	▪ Annual new vehicle registration number
Dependent Variable[\2]	▪ Bangkok population (registered number) ▪ Gross National Product per capita at 1988 price (GNP pct_1988) ▪ National Income per capita (NI pct) ▪ Gross Provincial Product of Bangkok at current market price (GPP_bkk) ▪ Fuel price ▪ New vehicle price

Remark: [\1] Depending on data availability
[\2] Data from National Statistical Office (NSO), Ministry of Information and Communication Technology, Thailand), see appendix J for collection of screening raw data

Table 4.9: The screening result for formulation of BVG model

Analysis variables	Correlation Score (1=show correlation)
Bangkok population	0.01
Fuel price (benzene & diesel)	-0.22/-0.08
New vehicle price	0.70
GNP pct. At 1988 price (GNP pct_1988)	0.72
GPP of Bangkok at market price (GPP_bkk)	0.60
National Income pct. (NI pct.)	0.10

Remark: shown as correlation score toward annual new vehicle registration number

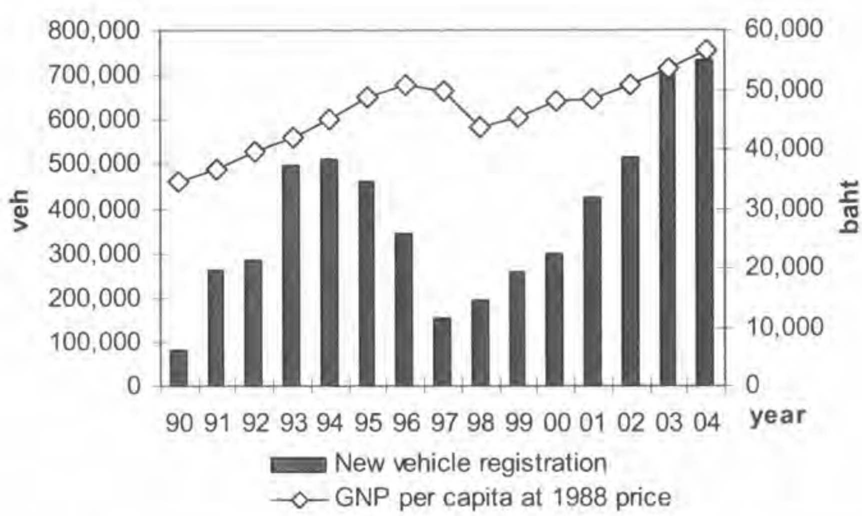


Figure 4.10: The relationship between Gross National Product per capita at 1988 price toward Bangkok annual new vehicle registration number

After correlation analysis has been conducted (result shown in table 4.8), the GNP pct at 1988 price (GNP pct_1988) is the highest correlation score while the next best score are new vehicle price and GPP of Bangkok at current market price (GPP_bkk), respectively. The lowest score is subjected to Fuel price (Benzene and Diesel) and Bangkok population that could be interpreted as converse relationship toward annual new vehicle registered number. Thus, based on the highest correlation score, the GNP pct_1988 is qualified and has been selected to estimate the model coefficient in the next part.

As a result of correlation analysis, the historical record of annual new vehicle registration number and GNP pct_1988 has been illustrated on figure 4.10. From the figure reveals obvious agreement for these 2 data sets. In economic point of view, the GNP per capita is often used as a measure of people's welfare compared against particular price at base year. The GNP could be calculated by gross domestic product (GDP) plus income earned by domestic residents through foreign investments and minus with the income earned by foreign investors in the domestic market. Therefore, GNP per capita can representing individual income of people earns in one year that having significant impact on annual new vehicle registration number (new vehicle purchased annually).

b) Estimation of Model Coefficient

According to equation of quasi-logistic function represent in equation 4.1, with aiming to focus on Bangkok region, the vehicle ownership per population *(C_t)* has been implied as ratio of number of vehicle registration in Bangkok per population *(P)*. The equation could be derived as following;

$$C_t = \frac{P}{1+e^{-a}X_1^{-b_1}X_2^{-b_2}.......X_n^{-b_n}} \qquad \text{(eq. 4.2)}$$

Where;

P is the ratio of BVRN per Bangkok population.

S is the saturation level of BVRN per Bangkok population

X_n are explanatory variables

a, b_n coefficient to be estimated

From equation 4.2, there is essential to estimate level of saturation *(S)* between BVRN and Bangkok population. Since Buttun et. al. (1993) given comments that developing countries (Thailand included) were still far from saturation level, the value of S can be only marginally sensitive or an upper boundary of vehicle volume that can not be exceeded by group of considering people in particular year. Therefore, an estimation of Bangkok saturation level *(S)* was conducted by reviewing of historical record of registered vehicle in Bangkok since 1989 and then S value was estimated by the projection the ratio of BVRN per Bangkok population (Ratio of P) to year 2015, the illustration shown in figure 4.10 as following;

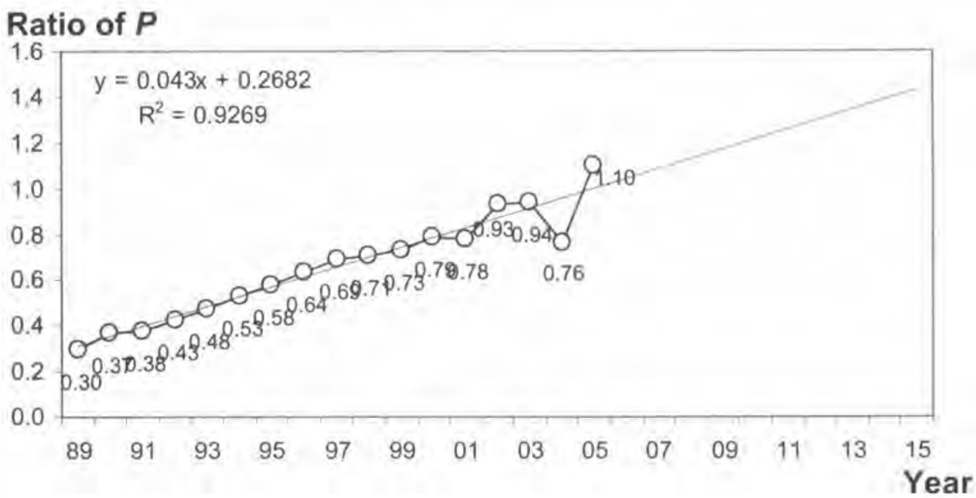


Figure 4.11: The projection of saturation level *(S)* to 2015.

As shown in figure 4.11, the ratio of P is dramatically increased since 1989 to 2003, ranged from 0.30-0.94 and then decreased to 0.76 in 2004 before sharpened rise again to 1.10 in 2005. As a result, the projection line shows that S value would not exceed 1.5 and this value has been used in equation 4.2. Then, GNP pct_1988 (*GNP*), number of years from 1989 (T) and saturation level (S) had been formulated and shown in equation 4.3 as following;

$$P = \frac{1.5}{1+e^{-a}\, GNP^{-b1}\, T^{-b2}} \qquad \text{(eq. 4.3)}$$

The estimation of model coefficient had been analyzed through non-linear analysis method by SPSS program version 14. The result of estimation shows in table 4. 10 below (see appendix K for SPSS results);

Table 4.10: The result model coefficients estimation for BVG model

	Coefficient	Std. Error	Adj. R-square
a	-2.120	0.175	0.926
b_1	0.017	8.733	
b_2	0.817	0.843	

At final stage, The Bangkok vehicle growth (BVG) model was formulated by combination of numerous coefficients, relevant explanatory variables. The operation form of model shown as follow;

$$P = \frac{1.5}{1+e^{2.120}\,GNP^{-0.017}\,T^{-0.817}} \qquad \text{(eq. 4.4)}$$

Where;

P is the ratio of BVRN per Bangkok population.

GNP is gross national product per capita (at 1988 price)

T is time variable (number of year from 1989)

To forecast future number of vehicle registration, the value of P must be taken from equation 4.4 and then multiplied with predicted Bangkok population at future simulation year. To demonstrate the model application, the assumption here had been laid on 5% growing of GNP per capita and 0.5% increasing of Bangkok population every year. The table 4.11 shows the estimated number of future vehicle registration in Bangkok predicted by BVG model.

Table 4.11: The prediction of Bangkok annual vehicle registration number by BVG model

	2007	2009	2011	2013	2015
GNP per capita\1 (ten thousand baht)	6.54	7.21	7.95	8.76	9.66
Bangkok population\2 (million)	5.71	5.77	5.83	5.89	5.95
Bangkok annual vehicle registration number (million)	5.28	5.50	5.71	5.91	6.09

Remark; \1 based on 5% growth of GNP pct; \2 based on 0.5% growth of Bangkok population

4.2.2 The Daily Traffic Localization (DTL) Model

At first stage of data analytical, the number of annual Bangkok vehicle registration and daily traffic of LAD and DIN that have been annually monitored-counting by Bangkok Metropolitan Authority (BMA) and illustrates in figure 4.11, As noticed from figure 4.12, the pattern of daily traffic and number of vehicle registered in Bangkok didn't show direct agreement relationship. So that the ratio of daily traffic (in LAD and DIN) toward BVRN have been analyzed and compared against value of *P* that calculated from BVG model, in order to specify relationship pattern of these considered parameters. The ratios of daily traffic (at LAD and DIN) towards BVRN and *P* have been shown in table 4.12 below.

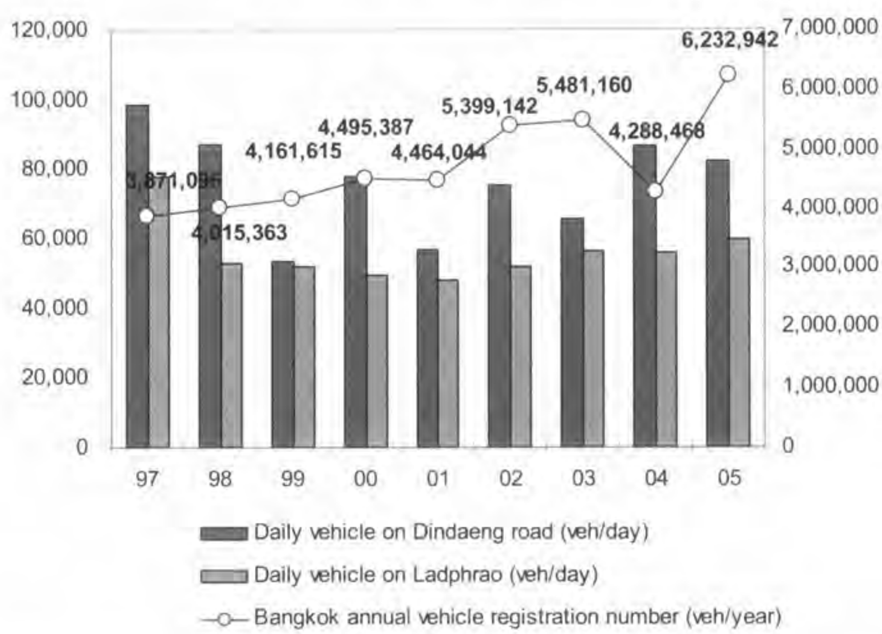


Figure 4.12: The number of vehicle registered in Bangkok and Daily traffic volume in LAD and DIN road

Table 4.12: The value of ratio of daily traffic to Bangkok vehicle registration number (BVRN) at LAD and DIN to *P* value

Year	1997	1998	1999	2000	2001	2002	2003	2004
LP_r	0.0201	0.0131	0.0124	0.0110	0.0107	0.0096	0.0102	0.0130
DD_r	0.0254	0.0216	0.0127	0.0173	0.0127	0.0139	0.0119	0.0202
P	0.6907	0.711	0.7349	0.7914	0.7796	0.9338	0.9378	0.7612

The LP_r is ratio of LAD daily traffic toward BVRN and DD_r is ratio of DIN daily traffic to BVRN as well as *P* is value taken from equation 4.4. Using scatter plot to create one-to-one relationship between x-y variable, the figure 4.13 has illustrated the results as follow;

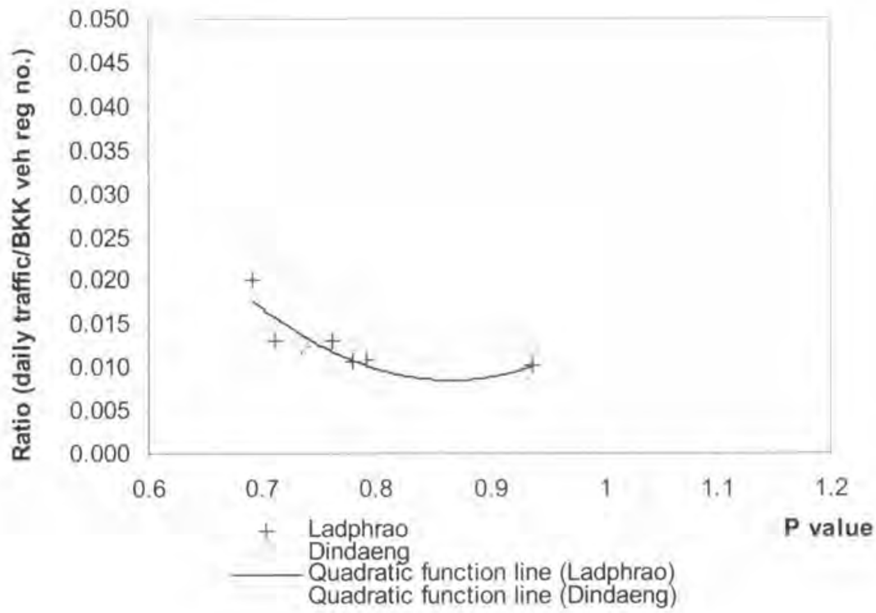


Figure 4.13: The one-to-one relationship of ratio of daily traffic to Bangkok vehicle registration number (BVRN) toward *P* value

Consider the figure above, the pattern of relationship between x and y variables trend to be in form of quadratic function. Therefore, the general equation of quadratic function could be expressed and shown in equation 4.5 below. In order to formulate Daily Traffic Localization (DTL) model with aiming to predict daily traffic in study road from future vehicle registration number (predicted by BVG model) the estimation of model coefficients using SPSS program (Curve Fit Method) need to be done. The result has shown in table 4.13

$$y = a + b(x) + c(x)^2 \qquad \text{(eq. 4.5)}$$

Where;

y is ratio of daily traffic toward BVRN

x is *P* value (ratio of vehicle registration number toward population)

a,b,c are coefficients to be estimated

Table 4.13: The result of model coefficients estimation for formulation of Daily Traffic Localization (DTL) model

	a	b	c	Adj. R-square
Ladphrao	0.234	-0.521	0.300	0.795
Dindaeng	0.263	-0.571	0.325	0.599

As result, the operational form of Daily Traffic Localization (DTL) model can be written as follow, whereas BKK_{pop} is Bangkok population (registered number).

DTL model for Ladphrao road………

Daily traffic = $[0.234 - 0.521(P) + 0.300(P^2)]\ [P * BKK_{pop}]$ (eq. 4.6)

DTL model for Dindaeng road………

Daily traffic = $[0.263 - 0.571(P) + 0.325(P^2)]\ [P * BKK_{pop}]$ (eq. 4.7)

However, there something to be noted that number of motorcycle has not been counted by BMA at first place, therefore on-site vehicle counting has been conducted on 11, 12-13 and 26-28 January 2006 to fulfill the missing data (see section 4.3 for detail). The percentage of motorcycle in LAD and DIN was carefully counted and put into estimation of all-typed vehicle on study road. The 3-days average of vehicle counting result and percentage of each vehicle type on both study roads are shown on table 4.14 and figure 4.14-4.15

Table 4.14: The number and percentage of each vehicle types on study roads

Vehicle type	Ladphrao\1		Dindaeng\2	
	number	percentage	number	Percentage
Sedan	38,805	46.71	47,493	44.55
Pick-up & Van	20,589	24.78	24,919	23.37
Tuk-tuk, 4-wheel taxi	568	0.68	1,056	0.99
Motorcycle	18,836	22.67	28,024	26.29
Minibus	497	0.60	599	0.56
6-8 wheels truck	669	0.81	1,499	1.41
10 wheels truck	120	0.14	212	0.20
Bus	3,000	3.61	2,813	2.64
Total	83,085	100.00	106,615	100.00

Remark: \1 the average 3-day data (11, 13-14 January 2006); \2 the average 3-day data (26-28 January 2006)

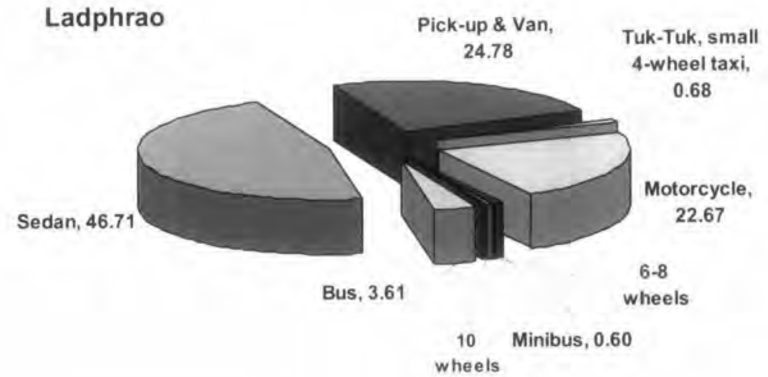


Figure 4.14: The percentage of vehicle type on LAD

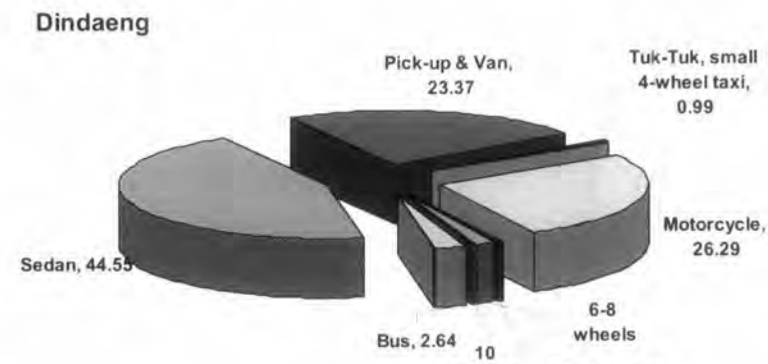


Figure 4.15: The percentage of vehicle type on DIN

As shown in figure 4.13 and 4.14, the percentage of motorcycle on LAD and DIN which have been counted during 11, 13-14 and 26-28 January 2006 (see section 4.3 for details) are 22.67% and 26.29%, respectively. To calculate daily all-typed vehicle (motorcycle is included), the percentage of motorcycle is need to be fill-in into equation 4.8 for calculation of daily all types of vehicle number that would occupy on LAD and DIN roads (using equation 4.9 and 4.10). As a result, the estimation of future daily traffic number that motorcycle is included, have been shown in table 4.15 that based on 5% increasing of annual GNP and 0.5% growing of Bangkok's Population every year

Daily traffic (all types)

= Daily traffic + [Daily traffic x Percentage of motorycle/100] (eq. 4.8)

For Ladphrao (LAD)……….

= Daily traffic + [Daily traffic x 0.2267] (eq. 4.9)

For Dindaeng (DIN)………..

= Daily traffic + [Daily traffic x 0.2629] (eq. 4.10)

Table 4.15: The prediction of daily traffic (all types) by DTL model

Road	2005	2007	2009	2011	2013	2015
Ladphrao	49,275	56,733	67,531	80,901	96,252	113,130
Dindaeng	78,103	86,064	97,723	112,237	128,957	147,383

Remark; based on 5% annual growth of GNP pct and 0.5% annual growth of Bangkok population

As the result shown in table 4.15, during 2007-2015, the LAD and DIN daily traffic would dramatically increase that derives from 49,275-113,130 vehicle/day and 78,103-147,383 vehicle/day on 2015, for LAD and DIN respectively.

4.2.3 Model Sensitivity Analysis

Because both BVG and DTL using same input variable which are GNP pct (at 1988 price) and time, therefore, models have been analyzed for sensitivity upon changing of GNP pct and time. The results given in daily traffic volume (vehicle/day) on LAD and DIN from 2007-2015. The GNP pct. was ranged between 0.5- 5.0 per annum while time derives from 2007-2015 and the results show in table 4.16 – 4.17

From sensitivity result, the number of daily traffic on LAD and DIN simulated by BVG and DTL model are highest at year 2015. The highest of number of daily traffic on LAD and DIN at simulated year 2015 are 113,130 and 147,383 vehicle/day, respectively. The relationship between increasing of GNP pct. and the number of daily traffic volume could be described as direct proportional relationship that the increased of daily traffic is directly affected by increasing of GNP pct.

Table 4.16: The sensitivity analysis of BVG and DTL model for LAD

GNP pct.	2007	2008	2009	2010	2011	2012	2013	2014	2015
0.5	56,512	61,405	66,995	73,196	79,931	87,132	94,742	102,709	110,988
1.0	56,537	61,446	67,056	73,279	80,040	87,270	94,912	102,913	111,229
1.5	56,562	61,486	67,116	73,362	80,149	87,408	95,081	103,116	111,469
2.0	56,586	61,527	67,176	73,445	80,257	87,545	95,250	103,319	111,708
2.5	56,611	61,567	67,236	73,527	80,365	87,682	95,418	103,521	111,947
3.0	56,635	61,608	67,295	73,610	80,473	87,818	95,586	103,723	112,185
3.5	56,660	61,648	67,354	73,691	80,581	87,954	95,753	103,924	112,422
4.0	56,684	61,688	67,414	73,773	80,688	88,090	95,920	104,125	112,659
4.5	56,709	61,728	67,473	73,854	80,795	88,225	96,086	104,324	112,895
5.0	56,733	61,767	67,531	73,935	80,901	88,360	96,252	104,524	113,130

Table 4.17: The sensitivity analysis of BVG and DTL model for DIN

GNP pct.	2007	2008	2009	2010	2011	2012	2013	2014	2015
0.5	85,833	91,107	97,154	103,880	111,199	119,039	127,334	136,029	145,074
1.0	85,859	91,150	97,218	103,969	111,316	119,187	127,517	136,249	145,334
1.5	85,885	91,193	97,282	104,057	111,432	119,335	127,699	136,468	145,593
2.0	85,911	91,236	97,346	104,145	111,548	119,482	127,880	136,687	145,851
2.5	85,937	91,278	97,409	104,233	111,664	119,629	128,061	136,904	146,108
3.0	85,962	91,321	97,473	104,321	111,780	119,775	128,241	137,121	146,365
3.5	85,988	91,363	97,536	104,408	111,895	119,921	128,421	137,338	146,620
4.0	86,013	91,405	97,598	104,495	112,009	120,066	128,600	137,554	146,875
4.5	86,039	91,447	97,661	104,582	112,123	120,211	128,779	137,769	147,130
5.0	86,064	91,489	97,723	104,668	112,237	120,356	128,957	137,983	147,383

4.2.4 Discussion and Concluding Remark

Bangkok Vehicle Growth (BVG) model

Among various theory of vehicle ownership, quasi-logistic function suggested by Buttun et. al. (1993) has been selected to construct Bangkok Vehicle Growth (BVG) model because of the readiness of data and objective suitability to this research. By analysis of explanatory variables, numerous of traffic-related variables were tested, only the Gross National Product per capita based on 1988 price (GNP pct_1988) showed highest score of correlation and has been used to formulate BVG model. In case of gross domestic product (GDP), this variable has been created to represent the growth of Thai's economic generated by Thai citizen and foreigner. Therefore, the individual foreigner's income that working in Thailand would been included into GDP value and may not appropriate to predict the growth of new purchased vehicle, at which could be owned and registered only by Thai people. Unlike GDP, the GNP could represent real Thai citizen income and obviously influence on new vehicle that have been purchased and newly registered every year. The coefficient estimation by SPSS running (nonlinear regression method) described the form of BVG as following where the confidence (justified from adjusted R^2) of prediction by this model is 92.6%

$$P = \frac{1.5}{1+e^{2.120}\, GNP^{-0.017}\, T^{-0.817}}$$

Where;

P is Bangkok vehicle registration number (BVRN) per population of Bangkok.

GNP is Gross National Product based on 1988 price

T is time variable from base year (1989)

By BVG prediction during 2007-2015, the Bangkok vehicle registration number would range from 5.28 – 6.09 million per year, respectively.

Daily Traffic Localization (DTL) model

With correlation of P value from BVG model, the quadratic function has been used to develop Daily Traffic Localization (DTL) model to calculated simulated daily traffic volume occupy on study road at simulation year. After models was configured with percentage of motorcycle from on-site vehicle count, the models was customized to predict daily all-typed vehicle volume showing in equation below; whereas BKK_{pop} is Bangkok population (registered number[1]) and P is calculated value from BVG model.

For Ladphrao (LAD):

$$\text{Daily traffic} = [0.234 - 0.521(P) + 0.300(P^2)]\ [P * BKK_{pop}]$$

For Dindaeng (DIN):

$$\text{Daily traffic} = [0.263 - 0.571(P) + 0.325(P^2)]\ [P * BKK_{pop}]$$

The confidence (justified from adjusted R^2) in prediction of DTL model to predict daily traffic volume on LAD is 79.5% and DIN is 59.9%. By the estimation result predicted by BVG and DTL model, Bangkok vehicle registration number (BVRN) would reach 6.09 million at 2015 while daily traffic on LAD and DIN would reach 113,130 and 147,383 vehicle/day on 2015, respectively.

From sensitivity analysis, the relationship between increasing of GNP pct. and the predicted number of daily traffic could be described as directly proportional relationship that volume of daily traffic is directly affected by increasing of GNP pct.

4.3 Simulation of Future Bangkok Air Quality

This section aims to provide basic assumption and configuration of TAPM in order to simulate future PM10 level in Bangkok which based on simulated traffic volume predicted by BVG and DTL model described in previous part. The concept and application of deterioration-applied emission factor (DET-EF) as well as process in calculation of emission rate have been clarified. The last three parts of this section describes the validation of simulated PM10, PM10 emission inventory and simulated level of PM10 at LAD and DIN during 2007-2015 generated by the models.

[1] To avoid the uncertainty due to fluctuated number of temporal residence in Bangkok (not registered population in BMA), the registered number of Bangkok population is applied in this research.

4.3.1 Basic Assumption

In order to simulate future Bangkok air quality, the basic assumption configured in the simulation procedure are essentially demanded that included model configuration, deterioration-rate emission factor (DET-EF), equation used for calculate PM10 emission rate and setting of meteorological file in worst case scenario. All these have been described as follow.

a) Model Configuration

The Air Pollution Model (TAPM) version 3.0 had been configured to predict roadside PM10 concentration at DIN and LAD road. Thus, dust mode has been selected and the resolution was set up at 25x25x25 grid number and 30, 10, 4 and 1 km for air pollution grid domain. The modeled data was compared against roadside monitoring data which operated on the same road governed by Pollution Control Department. The option of using meteorological assimilation had chosen; therefore, the hourly wind direction and wind speed at Queen Sirikit meteorological observation station was employed in model. The summary of model configurations are summarized and provided in table 4.18

Table 4.18: The configuration of TAPM for simulation of future Bangkok air quality

TAPM Parameters	Simulation setting
Number of grid point	25x25x25
Number of grid domain	4 domains
Resolution of grid domain	30, 10, 3 and 1 km.
Meteorological option	With assimilated data from SRK station
Air pollution option	Dust mode

b) Deterioration-applied Emission Factor (DET-EF)

The mathematic expression in calculation of deterioration-applied emission factor (DET-EF) can be given as equation 4.11. From equation, there are 3 factors that giving contribution to DET-EF, such as; zero kilometer emission level (ZKE), deterioration rate (DET) and accumulated kilometer (ACM-KM). Considering to equation 4.11, while the ZKE and DET value are static component, the ACM-KM is time variable component according to age of engine.

DET-EF = ZKE + (DET x ACM-KM/10,000) (eq. 4.11)

Where;

DET-EF = deterioration-applied emission factor

ZKE = zero kilometer emission level

DET = deterioration rate per 10,000 km

ACM-KM = accumulated kilometer (in odometer) for vehicle age at the selected simulation year

According to "PM abatement strategy for the Bangkok Metropolitan Area", the value of ZKE and DET has been introduced based on various vehicle types, and then these values were adopted in this research (Kishan et al., 1998). The detail summary of ZKE and DET for calculation of PM10 emission provides in table 4.19.

Table 4.19: The summary of PM10 emission level

Vehicle type	Model year grouping	ZKE (g/km)	DET (g/km/10,000 km)
Light-duty Gasoline vehicles	1960-1991	0.030	0.004
	1992-2020	0.005	0.003
Motorcycles	1960-1999	0.150	0.022
	2000-2020	0.071	0.013
Light-duty Diesel vehicles	1960-1996	0.150	0.008
	1997-2020	0.140	0.007
Heavy-duty Diesel-Trucks	1960-1996	1.20	0.050
	1997-1998	0.40	0.030
	1999-2020	0.17	0.010
Heavy-duty Diesel-Buses	1960-1996	2.16	0.040
	1997-1998	0.72	0.030
	1999-2020	0.31	0.015

Source: Kishan et al., 1998

According to equation 4.11, the DET-EF is direct proportion of ACM-KM or the distance that vehicle had traveled since purchased (shown as accumulated kilometer in odometer) while the ZKE could be noticed as static portion. Therefore, to quantify the DET-EF value, the ACM-KM needs to be calculated first relevant to their age of engines and the annual average vehicle travel (average VKT). For table 4.19 provides the average VKT classified by vehicle type as well as the mathematic equation solving the ACM-KM could be written in equation 4.12 as follow;

ACM-KM = Engine Age x Average VKT (eq. 4.12)

Considering equation 4.12, after average VKT in particular type has been known from table 4.20, the engine age of vehicle also demanded. This could be solved by taking the simulation year (the calendar year that do simulation) and then minus with the year that vehicle was registered. The equation expressed as follow;

Engine age = Simulation year - Registration year of vehicle (eq. 4.13)

Table 4.20: The summary of average vehicle travel (VKT)

Vehicle type	Average VKT/yr (km/yr)
Light-duty Gasoline vehicles	20,596
Light-duty Diesel trucks	18,075
Motorcycles	10,000
Heavy-duty Diesel Buses	48,000
Heavy-duty Diesel City trucks	40,000
Heavy-duty Long-haul trucks	120,000

Source: Kishan et al., 1998

c) Calculation of hourly emission rate

By model configuration described in table 4.15, model was set to predict hourly PM10 compare against hourly PM10 monitoring data. Thus, the input files (or lse file) calculated as hourly emission rate of PM10 is needed to be prepared for model simulation. The equation to quantify hourly emission rate can be divided into 4 steps as follow;

(1) Hourly emission rate (g/s)

$$= \sum_{i=1}^{n} \left[(\text{Emission from vehicle type}_i) \times (\text{road length}) \,/\, (\text{time conversion factor}) \right]$$

Where;

n = 5 (i.e. Light-duty Gasoline vehicle, Light-duty Diesel Vehicle, Motorcycle, Heavy-duty Diesel-Bus, Heavy-duty Diesel-Truck)

(2) Emission from vehicle type$_i$

$$= \sum_{1989}^{y} \left[(\text{Number of vehicle type}_i \text{ registered in year}_y) \times (\text{DET-EF of vehicle registered in year}_y) \right]$$

Where;

DET-EF = deterioration-applied emission factor

y = selected calendar year in model simulation

1989 = beginning year of vehicle data feed-in for simulation

(3) Number of vehicle type$_i$ registered in year$_y$

$$= \sum_{h=1}^{24} \left[\text{Number of vehicle type}_i \text{ travel in hour}_h\right] \times \left[\text{Percentage of vehicle type}_i \text{ registered in year}_y \text{ among summation of Bangkok annual new vehicle registration number for vehicle type}_i \text{ since 1989 to selected simulation year}_y\right]$$

The above equation could be written in-short as follow;

$$= \sum_{h=1}^{24} \text{NUM VEH}_{i,h} \times \text{\%VEH REGIS}_{i,\, y\_since\ 1989}$$

In order to quantify number of vehicle type $_i$ travel in hour $_h$ (NUM VEH$_{i,h}$) that occupy on DIN and LAD road. The data from on-site vehicle count is acquired in order to solve this equation. The detail of on-site vehicle count has been provided in the next part (vehicle profile) while the resolution for %VEH REGIS $_{i,\, y\_since\ 1989}$ is described in following step

(4) Percentage of vehicle type $_i$ registered in year $_y$ among summation of Bangkok annual new registration number for vehicle type $_i$ since 1989 to selected simulation year $_y$ (%VEH REGIS $_{i,\, y\_since\ 1989}$)

$$= \left[\text{vehicle type}_i \text{ registered in year}_y \times 100\right] / \text{summation of vehicle type}_i \text{ registered since 1989 to year}_y$$

The summation of vehicle type $_i$ registered since 1989 to year $_y$ could be determined from Bangkok historical data, and then summation number can be calculated to put into simulation. The historical data of each vehicle type registered annually in Bangkok since 1989 shows in figure 4.16

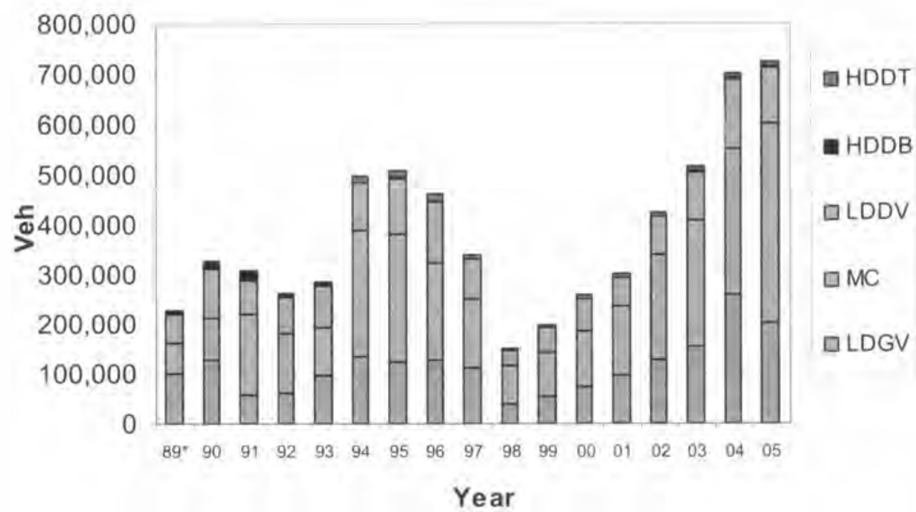


Figure 4.16: Distribution of annual new vehicle registration number since 1989
Remark: * estimated data

d) Vehicle profile

The objective of this operation is to determine vehicle profile (type and number) on DIN and LAD. These data assumed to remain constant for future year simulation and required for 'Number of vehicle type $_i$ travel in hour $_h$' for calculation of hourly emission rate (described in step 3 of earlier part). The on-site traffic count has planed to cover weekday (Mon-Fri) and weekend (Sat-Sun) of DIN and LAD road during 6.00 am - 8.00 pm recorded by Video Recorder, and then counted by manual checking to classify 8 vehicle types (sedan, pick up & van, tuk-tuk & small 4-wheel taxi, motorcycle, minibus, medium truck, heavy truck and bus – see appendix L for raw data). Finally, the data of all vehicle types has been re-grouped into 5 major classes (motorcycle, light-duty gasoline, light-duty diesel, heavy-duty diesel bus and heavy-duty diesel truck). The vehicle profile at LAD and DIN is illustrated in figure 4.17.

The identification of vehicle composition at LAD and DIN were shown in table 4.21. From the results, hourly vehicle number at DIN is larger than LAD for all counting date. The highest traffic volume on LAD and DIN both occurred on Friday (14 and 28 January 2006) as well as the second highest traffic volume were observed on Wednesday and Thursday (13 and 27 January 2006). The minimum traffic volume was found at LAD on Saturday 82,571 vehicle/day as well as the DIN on Saturday 87,766 vehicle/day.

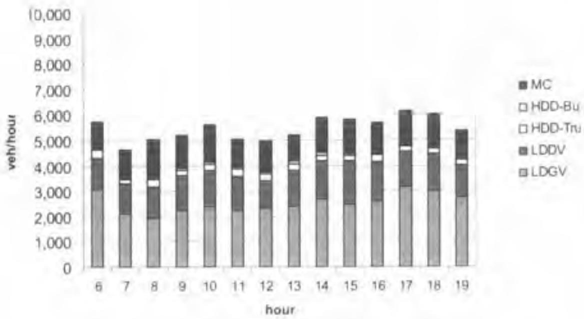


Figure 4.17A: 11 January 2006

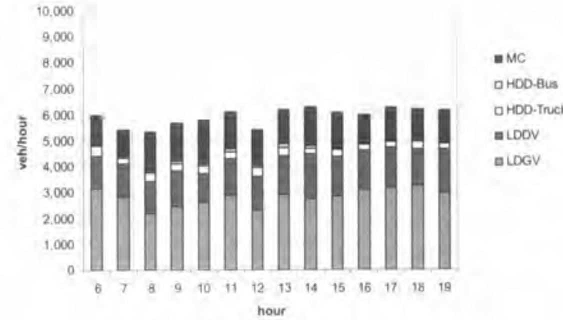


Figure 4.17B: 13 January 2006

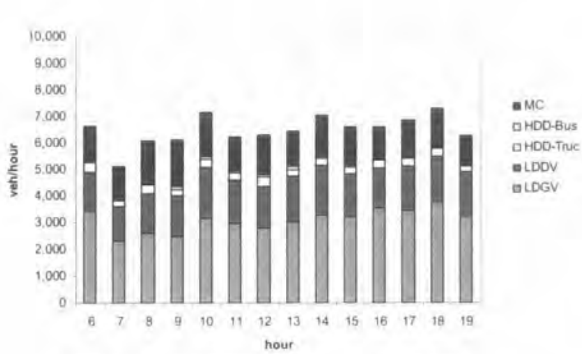


Figure 4.17C: 14 January 2006

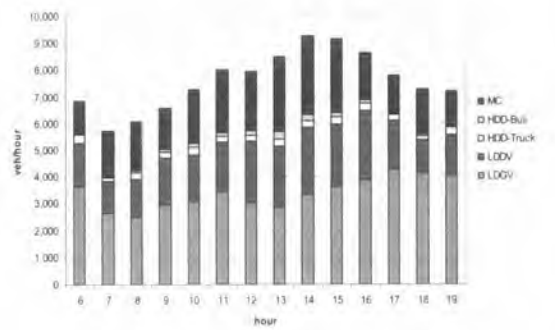


Figure 4.17D: 26 January 2006

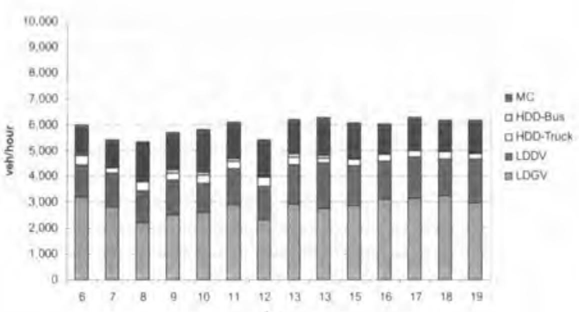


Figure 4.17E: 27 January 2006

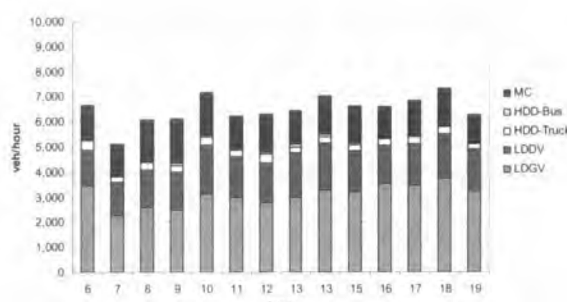


Figure 4.17F: 28 January 2006

Figure 4.17 Ladphrao and Dindaeng vehicle profile
(A-C): LAD hourly vehicle profile; (D-F) DIN hourly vehicle profile

Table 4.21: The daily number of vehicle type at LAD and DIN

Vehicle Type	LAD			DIN		
	11-Jan-06 (Wed)	13-Jan-06 (Fri)	14-Jan-06 (Sat)	26-Jan-06 (Thu)	27-Jan-06 (Fri)	28-Jan-06 (Sat)
Light-duty Gasoline	34,935	42,386	39,095	45,443	57,703	39,334
Light-duty Diesel	19,676	23,360	20,436	27,129	29,469	21,326
Motorcycle	17,672	20,152	18,685	28,573	32,732	22,767
Heavy-duty Diesel-Truck	725	810	832	1,754	1,855	1,523
Heavy-duty Diesel-Bus	3,294	3,675	3,523	3,428	3,992	2,816
Total	76,302	90,383	82,571	106,327	125,751	87,766

Table 4.22: The daily distribution (%) of vehicle type at LAD and DIN

Vehicle Type	LAD			Average 3 days	DIN			Average 3 days
	11 Jan 06	13 Jan 06	14 Jan 06		26 Jan 06	27 Jan 06	28 Jan 06	
Light-duty Gasoline	45.8	46.9	47.3	46.7	42.7	45.9	44.8	44.5
Light-duty Diesel	25.8	25.8	24.7	25.5	25.5	23.4	24.3	24.4
Motorcycle	23.2	22.3	22.6	22.7	26.9	26.0	25.9	26.3
Heavy-duty Diesel-Truck	1.0	0.9	1.0	1.0	1.6	1.5	1.7	1.6
Heavy-duty Diesel-Bus	4.3	4.1	4.3	4.2	3.2	3.2	3.2	3.2
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table 4.23: The LAD hourly vehicle profile

Time	Distribution of hourly traffic among daily traffic (%)	Distribution of vehicle type among hourly traffic (%)				
		LDGV	LDDV	MC	HDDT	HDDB
6.00-7.00	7.3	53.4	22.9	20.3	0.2	3.2
7.00-8.00	6.1	47.7	26.2	23.7	0.2	2.2
8.00-9.00	6.5	41.7	25.2	29.7	0.5	2.9
9.00-10.00	6.8	42.1	26.4	26.9	2.0	2.6
10.00-11.00	7.4	44.3	25.5	26.4	1.5	2.3
11.00-12.00	6.9	47.1	26.4	22.3	1.5	2.8
12.00-13.00	6.6	45.2	25.4	25.4	1.2	2.8
13.00-14.00	7.1	47.1	27.2	20.7	2.5	2.4
14.00-15.00	7.7	45.3	27.8	23.3	1.6	2.0
15.00-16.00	7.4	46.1	27.6	23.0	1.0	2.3
16.00-17.00	7.3	50.9	25.9	20.2	0.5	2.4
17.00-18.00	7.7	50.9	25.2	21.3	0.4	2.3
18.00-19.00	7.8	51.8	24.8	21.0	0.3	2.0
19.00-20.00	7.2	50.6	26.9	20.1	0.4	2.0

Remark: LDGV: Light-duty Gasoline Vehicle, LDDV: Light-duty Diesel Vehicle, MC: Motorcycle, HDDT: Heavy-duty Diesel-Truck and HDDB: Heavy-duty Diesel-Bus

Table 4.24: The DIN hourly vehicle profile

Time	Distribution of hourly traffic among daily traffic (%)	Distribution of vehicle type among hourly traffic (%)				
		LDGV	LDDV	MC	HDDT	HDDB
6.00-7.00	6.5	52.6	22.4	19.7	0.7	4.6
7.00-8.00	6.0	41.3	25.1	30.3	0.4	2.9
8.00-9.00	6.8	40.5	25.3	30.2	0.6	3.5
9.00-10.00	6.2	48.7	23.1	22.6	2.3	3.3
10.00-11.00	6.6	42.9	23.5	27.6	2.6	3.5
11.00-12.00	7.7	39.0	25.8	30.1	1.7	3.4
12.00-13.00	7.4	37.1	25.3	32.1	1.8	3.8
13.00-14.00	7.7	35.8	25.2	33.0	2.5	3.5
14.00-15.00	8.5	37.6	27.4	29.6	2.3	3.2
15.00-16.00	8.2	44.3	25.1	25.7	1.7	3.1
16.00-17.00	7.8	47.1	26.4	21.4	1.6	3.5
17.00-18.00	7.4	53.3	22.4	20.3	0.8	3.2
18.00-19.00	7.0	57.5	18.8	20.3	0.8	2.6
19.00-20.00	6.3	57.0	20.2	19.0	0.5	3.2

Remark: LDGV: Light-duty Gasoline Vehicle, LDDV: Light-duty Diesel Vehicle, MC: Motorcycle, HDDT: Heavy-duty Diesel-Truck and HDDB: Heavy-duty Diesel-Bus

The daily distribution of vehicle type at LAD and DIN is shown on table 4.22. To simulate hourly emission, the vehicle on LAD and DIN that refer to distribution of hourly traffic among daily traffic and distribution of vehicle type among hourly traffic are essentially need to be quantified, the data are shown on table 4.23 and 4.24, respectively.

e) PM10 background

As the basic need for model simulation, the level of particular air pollutants outside border of interest commonly known as 'background' level is needed to be clarified for interpreting of result. In general, the portion of background level may not combine into emission file. Thus, the concept in generating simulation results related to background level claimed in this research could be expressed as follow;

Simulation Results = Calculation by input data + Background level (eq. 4.13)

Where;

Input data = PM10 emission from vehicle at LAD and DIN

Background level = other sources of PM10 (except vehicle emission from LAD and DIN)

Analysis of PM10 background in Bangkok has been conducted by analysis of hourly PM10 monitoring data during the hour after mid-night (Sripraparkorn, 2001) at the outskirt and inner urban monitoring site. At Singharat (SING) station which located approximately 15 km at the South/West of the heart of Bangkok is selected to represent the outskirt urban monitoring data while LAD and DIN station located on the roadside of inner area of Bangkok's center are representing the inner urban monitoring site. The table 4.25 showed the monthly 24-hour average and 2-hour average (2.00-4.00 am) of PM10 from these selected monitoring stations during January.

Table 4.25: The monthly average PM10 at inner and outskirt urban monitoring station and distance from heart of Bangkok

Monthly level of PM10	**INNER**		**OUTSKIRT**
	DIN ($\mu g/m^3$)	**LAD ($\mu g/m^3$)**	**SING ($\mu g/m^3$)**
Average 24 Hrs	119.7	63.1	45.3
Average early morning (02.00-04.00 am)	109.4	59.8	43.6
Distance from heart of Bangkok (km)[\1]	1.25	6.90	>25

Remark; [\1] measured from victory monument; data obtained from PCD database during 2005-2006, for January data.

As shown in table 4.25, the level of PM10 at early morning average (2.00-4.00) am at all stations was lower than the average 24-hour of PM10 where SING showed the least difference between these two value. Considering early morning average, PM10 level derived from outskirt to inner area at range of 43.6-109.4 $\mu g/m^3$ where DIN was found at highest level but the lowest PM10 has been detected at SING. From the result, the level of PM10 shows inconsistency with time but reveals strongly correlation with distance from heart of Bangkok area where among these 3 monitoring stations, the distance of monitoring site from heart of Bangkok (from Victory Monument) derived from DIN, LAD and then SING (the farthest urban station). In the same way, high level PM10 at early morning hour derives from inner station (DIN and LAD) to SING where the lowest PM10 is found. This reveals that even though the least traffic dominated hour, background of PM10 seem to be independent from traffic volume but showed association with other sources of PM10 that located nearby the monitoring station. Since the real level of PM10 background governing over urban area has shown the needs of further investigation, this research would not combined these background into model results and leave model result to directly represent emission from these two study roads.

f) Worst case Scenario

To simulate future air quality in Bangkok, the worst case of meteorological condition was selected to simulate future year level of air pollutants. As for worst case scenario, the condition defined to the period of low wind speed (avg. < 1m/s) and dominated wind prevailing from Northeast direction that commonly occur at the middle of winter season (January). At during this period, monitoring data always confirmed that air pollutants, especially for PM10, are easily concentrated and exceeded the National Ambient Air Quality Standard influenced by dry humidity, low wind speed and shallow mixing high that normally occur in winter time. From 15-years of hourly meteorological data during January at SRK meteorological site at duration of 1991-2005, the averaged hourly wind direction ranged from the North and North-east direction (0-90^0) at early morning before shifted to the South and South-east direction at the afternoon until returned to the North again during the night. As for wind speed, the hourly wind speed derived from calm wind situation ($\leq$ 0.5 m/s) and then stronger wind prevailing occurs at the middle of the day (maximum at 2.7 m/s) before the speed was decreased again at the evening time ($\leq$ 1 m/s). The figure 4.18-4.19 demonstrated 15-years average hourly wind direction and wind direction as well as table 4.26 showed the range of meteorological data file setting for worst case scenario for the model simulation.

Table 4.26: The range of meteorological data file representing worst case meteorological condition for TAPM simulation

Hour	Wind Direction (degree)	Wind Speed (m/s)
1	0-90	≤ 0.5
2	0-80	≤ 0.5
3	0-70	≤ 0.5
4	0-70	≤ 0.5
5	0-70	≤ 0.5
6	0-70	≤ 0.7
7	0-70	≤ 0.7
8	0-90	≤ 1.0
9	0-90	≤ 1.5
10	10-120	≤ 1.5
11	10-120	≤ 1.5
12	20-150	≤ 2.0
13	30-160	≤ 2.5
14	40-180	≤ 2.5
15	40-160	≤ 2.0
16	30-150	≤ 2.0
17	30-150	≤ 1.5
18	30-150	≤ 1.5
19	20-130	≤ 1.5
20	10-120	≤ 1.5
21	10-100	≤ 1.0
22	10-90	≤ 1.0
23	0-90	≤ 0.7
24	0-90	≤ 0.5

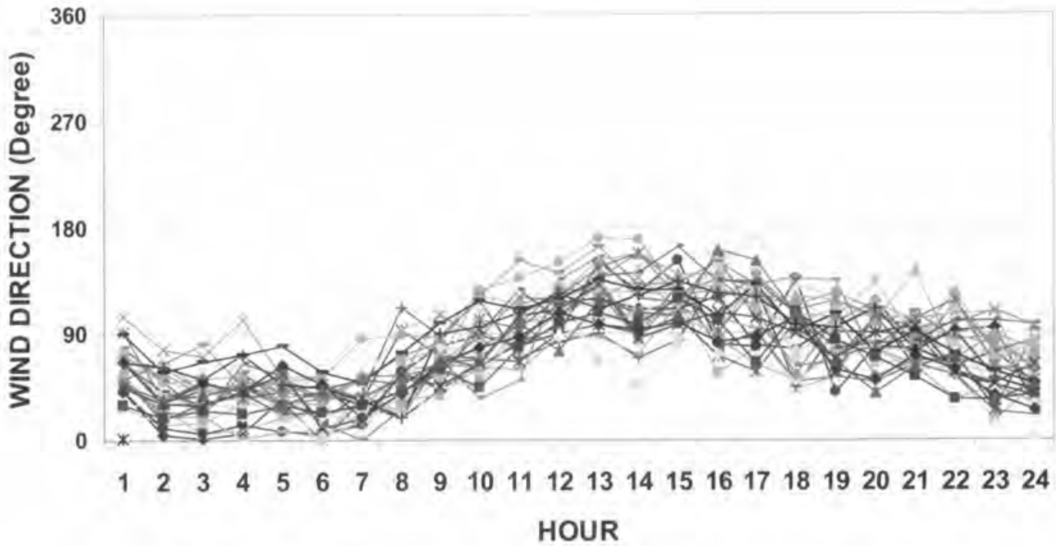


Figure 4.18: The average 15-year of hourly wind direction during January at SRK meteorological station
Remark: the colored lines represent 31 days in January

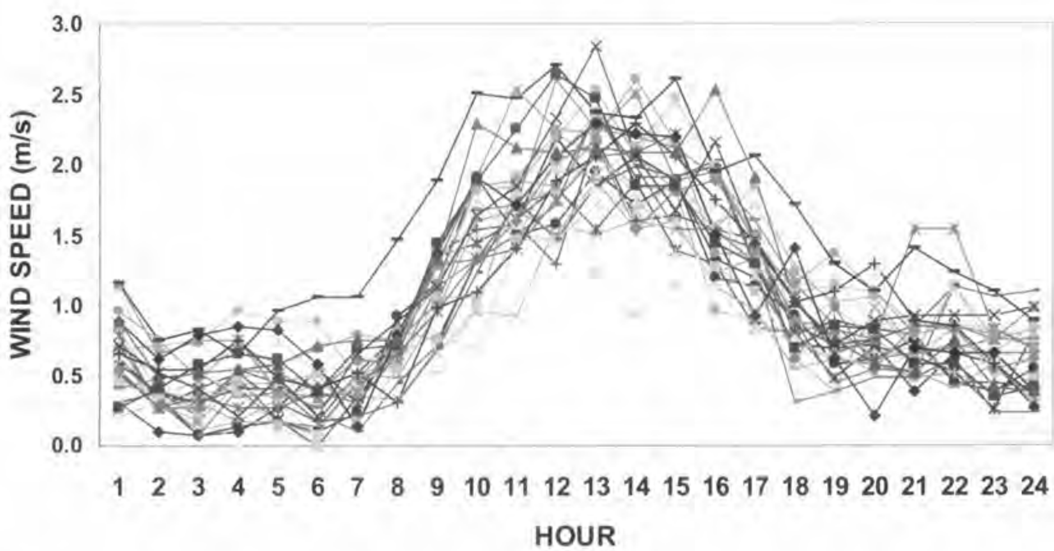


Figure 4.19: The averaged 15-year of hourly wind speed during January at SRK meteorological station
Remark: the colored lines represent 31 days in January

4.3.2 Validation of PM10 simulation

The observed meteorological data from SRK and data from on-site vehicle count, i.e., hourly vehicle profile and daily traffic volume, have been calculated for PM10 emission rate, and then, given to TAPM running. The simulated PM10 was compared against hourly monitoring PM10 at LAD and DIN at the same date of vehicle count. The table 4.27 and figure 4.20 have shown the 24-hour average of PM10 between monitoring and TAPM simulation.

Table 4.27: The 24-hour average of PM10 between monitoring and simulation

The 24-hour average of PM10	LAD			DIN		
	11 Jan 06	13 Jan 06	14 Jan 06	26 Jan 06	27 Jan 06	28 Jan 06
Monitoring\1 (µg/m3)	58.0	88.0	78.1	138.0	187.9	210.0
Simulation\2(µg/m3)	45.9	66.3	61.0	104.1	148.5	104.8

Remark: \1 www.pcd.go.th accessed on March 07, \2 not included background

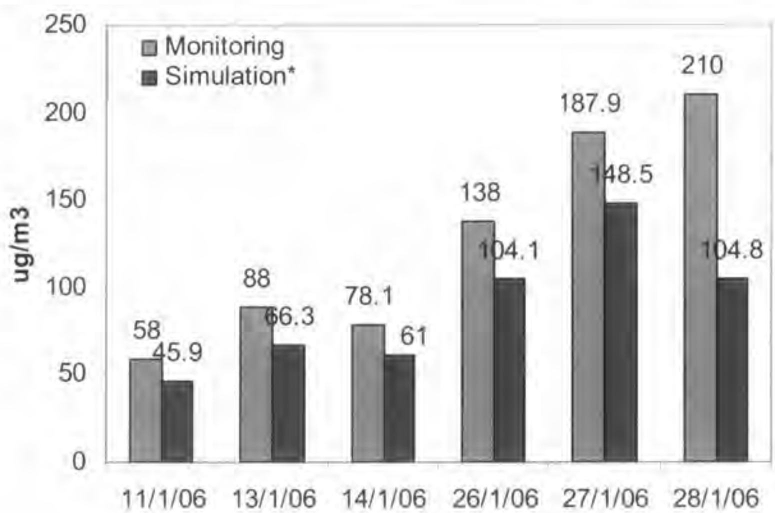


Figure 4.20: The 24-hour average of PM10 between monitoring and simulation
Remark: not included background

The monitoring PM10 at LAD and DIN were ranged between 58.0-210.0 µg/m3 where LAD and DIN were found the highest level on 14 and 28 January 2006, respectively. In part of simulated PM10 by TAPM, because the background level had not been included into the result, the simulated PM10 at all sites were lower compared to monitoring data but show agreement pattern with variation of monitoring data. The reason of under-predicted PM10 by model can be explained by influence of background level that could be assumed as dependent variable associated with local PM10 sources nearby monitoring site that have not been included into these simulation.

4.3.3 PM10 Emission Inventory from LAD and DIN

The essential part need to be known before running simulation is to know how much of PM10 emitted annually (known as emission inventory) by vehicle from LAD and DIN during 2007-2015. To calculate emission inventory, the BVRN is required from BVG and future daily traffic estimated by DTL model are demanded for these calculation, and then, brought into calculation procedures as described in 'calculation of hourly emission rate' (see section 4.3.1 for detail). The equation to calculate emission inventory is shown in equation 4.14 as well as table 4.28 and figure 4.20 provide details of each road link and the predictive PM10 emission inventory, respectively.

Emission Inventory (ton/year)

$$= \sum_{h=1}^{24} \left[\text{emission rate}_h \text{ (g/s)} \times \text{Unit Conversion Factor (from g/s -> ton/year)} \right] \quad \text{(eq. 4.14)}$$

Where;

emission rate $_h$ is PM10 emission of each road link from hour 1-24

Table 4.28: The length of each road link for calculation of PM10 emission inventory

Road	Road Link	Length (km)	Total length (km)
LAD	LAD 1&2	1.806	**6.891**
	LAD 3&4	1.320	
	LAD 5&6	2.445	
	LAD 8&9	1.320	
DIN	DIN 1&2	0.812	**4.128**
	DIN 3&6	1.316	
	DIN 4&5	2.000	

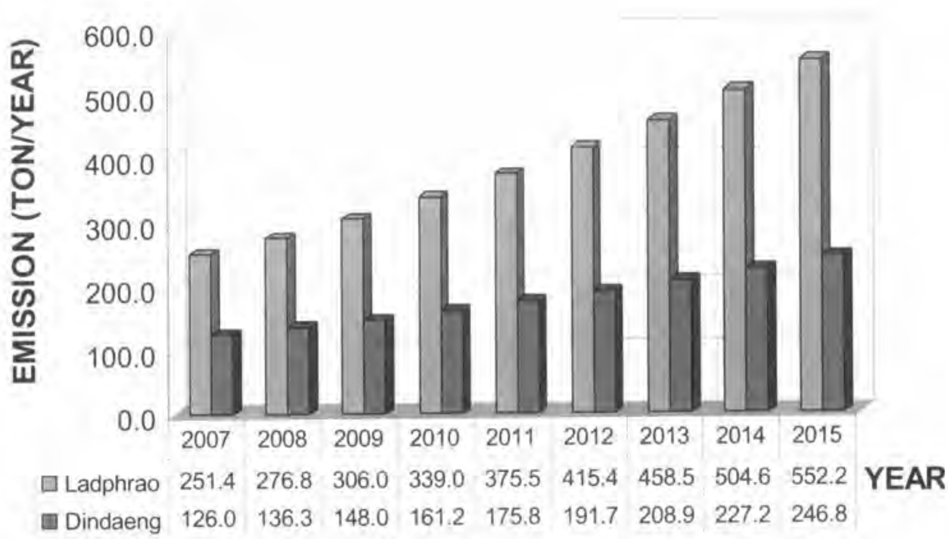


Figure 4.21: The future estimation of PM10 emission inventory at LAD and DIN

As shown in figure 4.21 above, the PM10 emitted from LAD during 2007-2015 would increase dramatically derive from 251.4-552.2 ton/year. Likewise, the PM10 emission from DIN would also increase dramatically in range of 126.0-246.8 ton/year. Something should be noted that because of length of LAD is longer than DIN and the amount of emission is directly subjected to length of road link. (see procedure to calculate 'hourly emission rate' page 93 for detail) Thus, this is why PM10 emission from LAD is greater than DIN even though level of monitored PM10 at LAD normally weaker than DIN.

4.3.2 PM10 Simulation for Future Year

Based on assumption described in section 4.3.1, TAPM was configured to simulate 24-hour average of PM10 through the input emission rate applied with DET-EF using hourly vehicle profile under worst case meteorological scenario (January data). The simulated result has shown in table 4.29 and figure 4.22 as following;

Table 4.29: The 24-hour average of simulated PM10 by TAPM

Year	The 24-hour average of simulated PM10 (μg/m^3)	
	LAD	DIN
2007	45.7	72.3
2008	49.6	77.9
2009	54.0	84.4
2010	59.0	91.6
2011	64.5	99.6
2012	70.4	108.2
2013	76.9	117.5
2014	83.7	127.4
2015	90.1	143.0

Remark: not included background

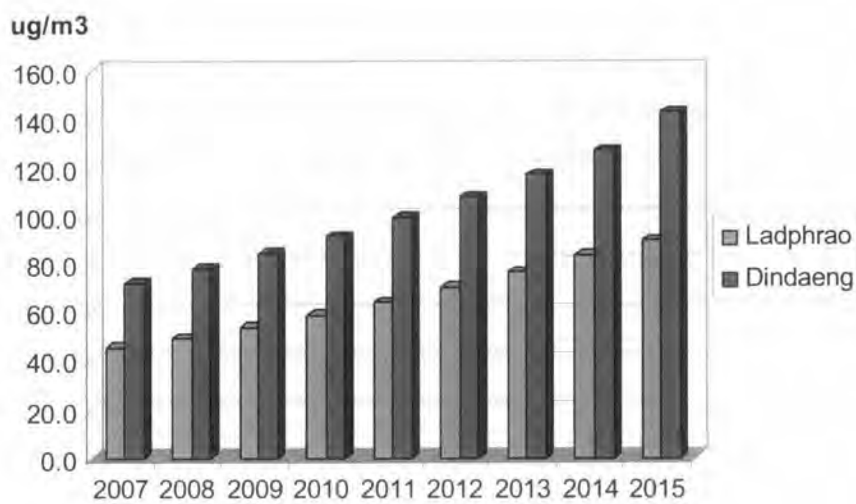


Figure 4.22: The future simulation of 24-hour average of PM10 at LAD and DIN
Remark: not included background

From the results, it is obvious that the simulated 24-hour average of PM10 during 2007-2015 in LAD would dramatically increase in range between 45.7-90.1 $\mu g/m^3$ as well as the DIN that also continuously rise deriving from 72.3-143.0 $\mu g/m^3$ until 2015. Moreover, it's should be note that level of simulated PM10 (not included background) at DIN would exceed the national air quality standard (120 $\mu g/m^3$) during year 2014-2015 that appropriate air management policy in preventing of this situation should be prepared in advance before the adverse health effect taking place.

4.3.5 Discussion and Concluding Remark

PM10 Simulation for Future Year

To simulate future air quality in Bangkok in period 2007-2015, the definition and calculation of deterioration-applied emission factor (DET-EF) have been clarified as well as the equations to quantify accumulated kilometer (ACM-KM) and engine age also discussed. According to high level of PM10 at roadside that occasionally exceeded the National Air Quality Standard, TAPM was configured to simulate future level of PM10. The four steps in estimation of hourly PM10 emission rate as essential input data (*lse file) required for model simulation have been provided. The fundamental needs for this estimation required several vehicle data such as, hourly vehicle profile (from on-site traffic count), number of Bangkok vehicle registration number (BVRN) since 1989, and the percentage of vehicle registration number among summation number of annual vehicle registration since 1989.

The determination of PM10 background has been analyzed from monitoring data at inner urban monitoring site (LAD and DIN) and outskirt monitoring site (SING). The analysis focused on the difference of 24-hour average of PM10 and average early morning hour (2.00-4.00 am) of PM10 when traffic showing least dominant to monitoring data. From the results indicated that level of PM10 during early morning hour were varied upon distance of monitoring site from heart of Bangkok, the level of PM10 was being low at outskirt station (SING), and then continually increased for inner urban station (LAD and DIN), whereas level of PM10 at this period was derive in range of 43.6-109.4 $\mu g/m^3$from SING to LAD and then DIN, consequently. This can be interpreted that PM10 background is dependent variable showing association with other sources of PM10 (except traffic emission from LAD and DIN) nearby the monitoring site rather than variation of traffic volume on study roads at particular hour.

PM10 Emission Inventory from LAD and DIN

The PM10 emission inventory using input from BVG and DTL model for LAD and DIN at simulation year during 2007-2015 has been provided. The simulation was conducted base on emission from each road link, and then making projection to future year. On 2015, the PM10 emission from LAD and DIN would reach to 552.2 and 246.8 ton/year, respectively. There is something should be noted that the emission of Ladprhao is being larger than DIN even though monitored PM10 at LAD normally lower than DIN. The reason to explain these could be described that because of length of LAD road is longer (6.9 km) while DIN is only 4.2 km. In principle, the emission inventory is direct proportion length of road (unit expressed in g/km). Therefore, longer road length would generate more emission.

In prediction of future PM10 level by TAPM based on emission inventory calculated from earlier part. The simulated 24-hour average of PM10 from 2007-2015 in LAD would in ranged of 45.7-90.1 $\mu g/m^3$ and DIN derives from 72.3-143.0 $\mu g/m^3$. There is a note that level of simulated PM10 (not included background) at DIN would exceed the national air quality standard (120 $\mu g/m^3$) during 2014-2015. For air management point of view, the appropriate air management policy focused on traffic-induced air pollution should be enforced and applied on DIN in order to protect future air quality.

4.4 The Model Analysis of Bangkok Air Quality Management Policy (BAQMP)

4.4.1 The Assumption on Policy Approach

According to annual air quality monitoring report by the Pollution Control Department (PCD) of Ministry of Natural Resources and Environment, the level of PM10 has occasionally exceeded The National Air Quality Standard (120 $\mu g/m^3$) particularly on roadside area. The main sources of PM10 on roadside area have been confirmed that vehicle emission is major source of contribution. Therefore, in order to reduce adverse effect from PM10, several approaches of traffic management and vehicle emission policy have been listed. The assumption based on various approaches also described in table 4.30

The first approach is policy that dealing directly on vehicle composition. Since there is no reliable evidences on how much vehicle profile impacted by particular policies, the various assumptions have been made in order to quantify percentage of PM10 reduction from potential policy. The extension of mass transit network (i.e., elevated sky train or sub-way) is assumed to decrease traffic volume about 10% from daily occupying vehicles due to more transfer efficiency generated by extended network. The car pool policy is proposed here based on assumption that light-duty gasoline vehicle (sedan) would be decreased about 10% during rush hour at morning and evening peak because commuters travel together with the same car. For introducing of bus lane policy, the assumption made by 10% of light-duty gasoline vehicle (LDGV) replacing by heavy-duty diesel bus (HDDB) in ratio of 3:1 (LDGV:HDDB) during rush hour. To prohibit heavy-duty diesel truck (HDDT) in day time, policy is assumed to reduce amount of truck to zero at period of 6.00 am – 8.00 pm to avoid traffic congestion associated with truck traveling.

The second approach is introduced for dealing with reduction of emission from vehicle. The assumption made that amount of vehicle occupying on traffic surface in Bangkok would have been forced to install with EURO III engine (for gasoline vehicle) and EURO IV (for diesel vehicle) suggested by National Atmospheric Emission Inventory (NAEI), UK. The amount of vehicle proposed here are 10%, 50% and 100%, respectively.

4.4.2 Policy Analysis

The model has been used as a tool to evaluate performance of the proposed policies on air pollution reduction. The model was configured with worst case meteorological condition (January dataset) to simulated PM10 concentration on LAD and DIN road. The calculation of percentage of PM10 reduction has been compared against level of PM10 simulated for 2007 (base year) under following equation and the result showed in figure 4.22 as follow;

Table 4.30: The assumption behinds policy approaches.

Policy Approach	Assumption
1) Policy on vehicle composition	
1.1) Extension of mass transit network	10% decreasing of daily traffic
1.2) Car pool	10% decreasing of LDGV in rush hour (6.00-9.00 am, 5.00-7.00 pm)
1.3) Bus lane	10% of LDGV replaced by HDDB (in ratio LDGV:HDDB = 3:1) at rush hour (6.00-9.00 am, 5.00-7.00 pm)
1.4) No truck traveling in day time	0% of HDDT during day time (6.00 am – 8.00 pm)
2) Policy on vehicle emission	
2.1) 10% Euro III (gasoline) and Euro IV (diesel)	PM10 Emission Factor[\1] (g/km) LDGV = 0.0007 LDDV = 0.044 HDDB = 0.044 HDDT = 0.064
2.2) 50% Euro III (gasoline) and Euro IV (diesel)	
2.3) 100% Euro III (gasoline) and Euro IV (diesel)	

Remark: [\1] Source: National Atmospheric Emission Inventory (NAEI), UK (see appendix M for detail)

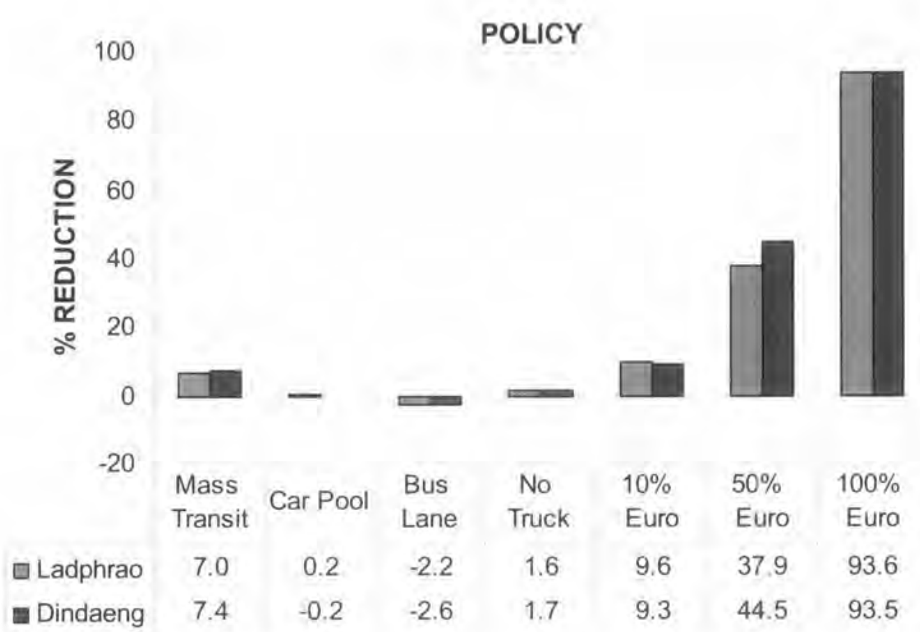


Figure 4.23: The percentage of PM10 reduction upon proposed policy
Remark: percentage of reduction from base year (2007)

Percentage of PM10 Reduction (%)

$$= \frac{[\text{Simulated PM10}_{base\ year} - \text{Simulated PM10 of Policy}_p] \times 100}{\text{Simulated PM10}_{base\ year}} \qquad \text{(eq. 4.15)}$$

Where;

Simulated $\text{PM10}_{base\ year}$ = level of PM10 simulated by TAPM on year 2007
Simulated PM10 of Policy_p = level of PM10 simulated by TAPM under assumption based on proposed policy

From figure 4.23, percentage of PM10 reduction simulated by TAPM reveals that the most effective policy are on those policies that focus on vehicle emission reduction (EURO III and IV). The simulation also shows that Bus Lane is not an effective policy because increasing number of bus (in bus lane) during rush hour would remain generating PM10 to urban atmosphere. For extension of mass transit system, the daily vehicle (all types) assumed to be reduced about 10%, percentage of reduction reached about 7% for study, these confirmed that decreasing of existing traffic by extension of mass transit transfer system would be advantage for air quality standing point. For car pool policy, because commuters travel together in same care during rush hour and assume to decrease 10% LDGV (or sedan) during rush hour. It can be noticed that LDGV vehicle is being less influence (±0.2%) on PM10 reduction compared to HDDB/HDDT (note that PM10 emission from LDGV is accounted only 1.5% of HDDB emission and 1.09% of HDDT emission). Therefore, this policy did not provide significant improvement on PM10 reduction.

4.4.3 Discussion and Concluding Remark

Policy Analysis on Bangkok Air Quality Management Policy (BAQMP)

The policy analysis has been tested by simulation of TAPM based on various assumption in each policy approaches. The simulated PM10 from each policy has been compared with simulated PM10 on year 2007, and then calculated for percentage of PM10 reduction. From the result, the most effective approaches are the policies that directly deal with reduction on vehicle emission not vehicle composition. The simulation also reveals that only 10% of vehicle operated in EURO III and IV on study roads, the pollution in future year would be reduced to 9.6%. Therefore, by the result of this research, the recommendation for the Bangkok Air Quality Management Policy (BAQMP) is subjected to the approach of vehicle emission reduction policy. However, any policy that can reduce daily traffic volume on particular road such as, the extension of mass transit transfer system that shows significant improvement in PM10 reduction would be recommended as well.

The other potential example of vehicle emission reduction policy is the promotion of engine powered by LPG/NGV fuel. While NGV is natural gas under pressure above 3,600 pounds per square inch but LPG is natural gas in liquid form. The natural gas has been suggested to apply as urban abatement measure according to efficiency in PM10 reduction (Torp, C., and Larssen, S., 1996). From recent research indicated that NGV fuels also support vehicle emission reduction on CO, CO_2, Hydrocarbon (HC) and NO_x compared to gasoline (Aslum, M.U. et al., 2006). Therefore, the attempt in promotion of LPG/NGV is considerably worthwhile to propose in Bangkok Air Quality Management.

Limitation of this research

In order to apply these policies for future purpose, there are some limitations driven by assumption in simulation process that need to be addressed. Because the result in policy analysis directly depending on future PM10 emission inventory from LAD and DIN, at which future traffic growth (by estimation of BVG and DTL model) is strongly associated. However, there is uncertainty on unexpected factors that may not be captured by BVG and DTL and need to be aware; for example, economic crisis, oil/fuel shortage causing by war, economic instability due to political crisis and terrorist activities. Moreover, assumptions on future vehicle profile (hourly percentage of all vehicle type at LAD and DIN) and saturation level of vehicle ownership in Bangkok would recommended to change if more updated data is available in the future. For saturation level of Bangkok vehicle ownership, the usefulness of advanced traffic model could probably provide more realistic value than the estimation from statistical data.

In case of air pollution management, this research proposes the policies which focused only on PM10 reduction. However, there is remaining problem especially on ozone (O_3) that exceeded the National Ambient Air Quality Standard in some area of Bangkok (PCD, 2005). Due to photo-chemical reaction associated with volatile organic carbon (VOC) and nitrogen oxide (NO_x) generating secondary-typed of air pollutant O_3. From EU experiences (Fenger, 1999 and EU Commission, 1996), numerous countries have agreed on vehicle emission legislation and fuel standard dealing with reduction of NO_x emission from vehicle such as, induction of 3-way catalytic converters. Therefore, for Bangkok situation, the promotion of catalytic converters should be considered to be enforced for both new and old vehicle in order to mitigate this problem.