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A PREDICTIVE STUDY: CARBON MONOXIDE EMISSION MODELING AT A SIGNALIZED INTERSECTION

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Abstract

CAL3QHC dispersion model was used to predict the present and future carbon monoxide (CO) levels at a busy signalized intersection. This study attempted to identify CO "hot-spots" at nearby areas of the intersection during typical A.M. and P.M. peak hours. The CO concentration "hot-spots" had been identified at 101 Commercial Park and the simulated maximum 1-hour Time-Weighted Average (1-h TWA) ground level CO concentrations of 18.3 ppm and 18.6 ppm had been observed during A.M. and P.M. peaks, respectively in year 2006. This study shows that there would be no significant increment in CO level for year 2014 although a substantial increase in the number of vehicles is assumed to affect CO levels. It was also found that CO levels would be well below the Malaysian Ambient Air Quality Guideline of 30 ppm (1-h TWA). Comparisons between the measured and simulated CO levels using quantitative data analysis technique and statistical methods indicated that CAL3QHC dispersion model correlated well with measured data.

Keywords: CAL3QHC dispersion model, Carbon monoxide, Maximum average, Peak hours, Signalized intersection.

1. Introduction

Transportation activities have been identified as one of major source of air pollution in urban areas [1-3] with subsequent adverse human health effects [4, 5]. Signalized intersections generate relatively large volumes of traffic, particularly during rush hours when traffic typically circulates at low speeds with frequent stops and starts. This traffic pattern produces relatively high CO emissions. According to Claggett et al. [6], the ambient concentration of CO resulting from vehicular traffic might be high near locations where vehicles trend to accumulate, slow down, and idle for a

Nomenclatures

1-h TWA	1-hour time-weighted average
G	Vehicle growth rate
V	Number of vehicle

period of time. The extent of this problem is a direct function of the number of vehicles, their operating mode, their movement, and the length of delay. Sensitive stationary receptors within the surroundings of a signalized intersection such as commercial area, schools, residential flats and apartments and other public places are also a concern over the effect of traffic-related emissions on health and the local environment. These concerns have contributed to the demand for a sustainable city development for the management of transportation planning and urban air quality.

Motor vehicles make a significant contribution to the atmospheric pollution inventory, contributing over 90% of CO emission in the urban area [7, 8]. This particular pollutant has also been the target of investigation in most monitoring and modeling studies concerning vehicular pollution near roadways and major intersections in many cities [9, 10]. CO is the result of incomplete fuel combustion that characterizes mobile as opposed to stationary pollution sources and therefore it can be used as an indicator for the contribution of traffic to air pollution [11, 12].

Study of air quality problems at the micro-scale urban environment requires application of an adequate methodology that permits the understanding of the source-receptor relation and to develop a proper strategy to reduce atmospheric pollution [13, 14]. Air dispersion models have been widely used to address this issue as these models play an important role by providing information for better and more efficient air quality planning. For example, line source models are used to simulate the dispersion of pollutants near highways where vehicles are continually emitting pollutants. In the present work, CAL3QHC dispersion model was used to model and predict CO concentrations at Mabel Signalized Intersection, Kuching for years 2006 and 2014 during A.M. (07:00-09:00) and P.M. (17:00-19:00) peaks. The primary objective is to identify CO concentration hot-spots during typical peak hours at Mabel Signalized Intersection and to assess the receptors exposure and evaluate the compliance of the predicted level of pollutants with the Recommended Malaysia Air Quality Guidelines. Exposure to CO on selected receptors in the vicinity of the study area is also discussed.

2. Material and Methods

2.1. CO emission modeling

Computer simulations using CAL3QHC (Version 2) dispersion model were carried out to predict CO concentrations, C(x) from motor vehicles at roadway intersections. The model is a line source air quality model developed by the California Department of Transportation (Caltrans). The model is predominantly based on Gaussian diffusion equation and employs a mixing zone concept and a traffic algorithm to characterize pollutant dispersion over the roadway. CAL3QHC is practical for estimating queue lengths and the contribution of emissions from both moving and idling vehicles near signalized intersections.

CAL3QHC automatically sums the contributions from each link and queue to a certain receptor. Surface roughness and meteorological variables (such as atmospheric stability, wind speed, and wind direction) can usually be assumed constant in the area understudy [15]. A free-flow link is defined as a straight segment of roadway having a constant traffic volume, width, travel speed, height, and vehicle emission factor. The link speed for a free-flow link speed represents the speed of vehicle traveling along the link in the absence of the delay caused by traffic signals. CAL3QHC assumes that vehicles are in idling mode of operation only during the red phase of the signal cycle. It calculates the emission source strength based on the idling emission rate, the number of lanes of vehicles idling at the stopping line, and the percentage of red time. The output of the dispersion model is 1-h average CO concentration at the receptors. The non-vehicle-originated (background) concentration of CO at modeled site was 0.2 ppm, which was estimated using the simplified equation by [16]. Table 1 lists a sample of typical input variables to CAL3QHC.

Table 1. Primary Input Parameters for CAL3QHC.

Variable	Parameter
Meteorological	• Wind Class • Wind speed/Settling velocity (m/s) • Mixing Height (m) • Averaging time (min) • Stability Class (1 to 6 = A to F) • Surface Roughness coefficient (cm)
Site	• Roadway coordinates [*x*, *y*, *z*] (m or ft) • Roadway Width (m or ft) • Receptor coordinates [*x*, *y*, *z*] (m or ft)
Traffic	• Traffic volume [each link] (veh/h) • Traffic speed [each link] (mi/h) • Average signal cycle length [each intersection] (s) • Average red time length [each approach] (s) • Clearance lost time (s) • Saturation Flow Rate (veh/h) • Signal Type: [1] = Pre-timed, [2] =Actuated, [3] = Semi-actuated • Arrival Type [1] = Worst progression, [2] = Below average progression, [3] = Average progression, [4] = Above average progression, [5] = Best Progression • Level-of-Services [A to F] or “LOS [A to F]”
Emission Factor	• Composite running emission factor [each free flow link] (g/veh-mi) • Idle Emission factor [each queue link] (g/veh-h)
CO concentration level	• CO concentration (ppm) • Background CO (ppm)

2.2. Description of experimental sites

Kuching, located in the State of Sarawak, Malaysia is a rapid developing city with an estimated population of approximately 600,000. The major commercial and business activities are concentrated in the city center [3]. A study was carried out to predict the present and future carbon monoxide (CO) levels at a signalized intersection - Mabel Signalized Intersection in Kuching City (Fig. 1). It is a highly demanding channelized intersection for motor vehicles because it links to most of the working and commercial areas from Kuching City centre and Samajaya Free Industrial Zone (SJFIZ) to Kota Samarahan, Batu Kawa New Township and Kuching International Airport (KIA) (Fig. 1). Assessments (field measurements and computer simulations) on correlationship of carbon monoxide (CO) pollution and transportation activities were carried out, in addition to micro-scale analysis in the immediate vicinity of Mabel Signalized Intersection.

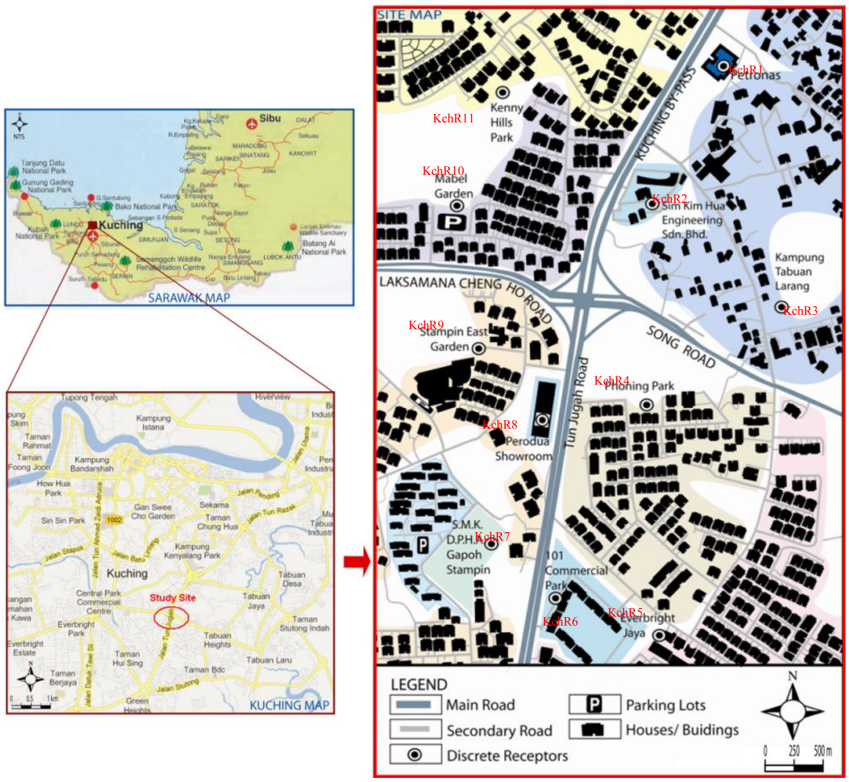

Fig. 1. Location of Mabel Signalized Intersection, Kuching.

2.3. Field measurements

The CAL3QHC simulated outputs were evaluated against CO levels measured at eleven (11) field monitoring sites or Discrete Receptors (Fig. 1). CO levels were measured using M40 Multi-Gas Monitor manufactured by Industrial Scientific, U.S.A.; a continuous CO monitoring unit with detection range of 0-999 ppm. M40 was calibrated using 0.5 L/min gas from a cylinder containing mixture of 100 ppm CO prior to conducting field measurements. It was equipped with a continuous loop data logger with memory size storing up to 50 hours of data for all four sensors, including ambient temperatures. The monitoring instrument was positioned at about 1.5 m above the ground and at $\geq$3 m from the road shoulder.

The measurements were conducted continuously for 12 hours (07:00-19:00 hours) with 1-h time weighed average (TWA).

2.4. Roadside enumeration/ spot count

Roadside enumeration was carried out simultaneously with roadside interviews at Mabel Signalized Intersection to determine total number of passing-by vehicles. Traffic counting was carried out by using “Tally Sheet” model to ensure that every surveyor can record 3 types of vehicles at the same time. Motor vehicle counting in the field was carried out continuously for different categories of vehicles (i.e., heavy duty, light duty petrol and diesel) from all directions. Every surveyor was provided with a manual counter for the passing-by vehicles. The average numbers of motor vehicles passing by each of the monitoring sites were between 1,309 – 4,890 vehicles/h. The average vehicle speed was in the range of 20-50 km/h. MOBILE 5a was used to generate traffic source emission factors as inputs to CAL3QHC.

2.5. Traffic volume study

Fieldwork was conducted to evaluate the characteristics of traffic flow and patterns at the intersection, with emphasis on the capacity of the road to determine the number of vehicles, direction of traffic movement and classification. Fieldwork was primarily aimed at assessing the current traffic patterns or characteristics, and attempted to correlate present with future traffic demand.

In this study, traffic volumes were compiled in daily and peak hours, even though Average Daily Traffic (ADT) and Annual Average Daily Traffic (AADT) are generally used for long-term monitoring. Traffic counts were conducted during morning and afternoon peak hours. In this case, A.M. hours of 07:00-09:00 and P.M. hours of 17:00-19:00 were taken as the typical peak hours.

2.6. Intersection study

Generally, the primary objective of traffic study at an intersection attempts to assess the extent of traffic delays and accident occurrences and to recommend suitable measures to overcome the deficiencies. However, this study aims to assess CO emissions at a signalized intersection. During fieldwork, turning movements of all vehicles were also recorded at each of the intersections during the two peak periods.

2.7. Travel time survey

Travel time or travel speed survey was carried out to determine the average overall route speed of each of the segments of the research area’s road network, as these data are indispensable to execute the dispersion model. Measurements were made from a car traveling at speed permissible by the traffic stream, and the information collected for the travel time survey included journey time, delays, traffic queuing time, traffic clearances time and length of road section.

2.8. Arrival type/rates survey

There are five (5) types of arrival rates which can be specified in CAL3QHC: (i) the worse progression (dense platoon at the beginning of red time); (ii) below average progression (dense platoon during the middle of red time); (iii) average progression (random arrivals); (iv) above average progression (dense platoon during the middle of green time); and (v) best progression (dense platoon at the beginning of green time.)

Traffic operations were assumed to improve as progression improved. In this study, the default arrival rate in CAL3QHC and average progression were used. Additionally, one second of lost yellow time (i.e., yellow idling time not used for vehicle movement) was applied to all phases.

2.9. Meteorological data

A portable meteorological weather station (ESM Model 900) was installed at the monitoring sites to monitor continuously the wind speed, wind direction, temperature and humidity. Meteorological data were obtained from Kuching International Airport Meteorological Station managed by Malaysian Meteorological Service Department to determine the atmospheric stability classes.

2.10. Forecasting future CO emissions in year 2014

Predicted CO emissions in future or forecasting years were generated by using CAL3QHC dispersion model. For this study, two assumptions were made:

- There was no significant change in geological, climate and site variables; and
- Background CO and traffic variables (traffic flow, traffic volume and so on) were the primary variables in this predictive study.

Predictions on future background CO levels had been carried out by using the existing observed or monitored background CO levels, and the projected vehicle growth rate. Predicted future traffic volumes were generated using vehicle growth rates supplied by Road and Transportation Department of Sarawak, Malaysia. Predicted mean total vehicles in forecasting years were estimated by using Eq. (1):

$$V_{forecasting} = V_{monitored} \times G \tag{1}$$

where, G is vehicle growth rate, $[G = (1.0798)^{nYEAR}]$

Background CO calculations were calculated based on the derivative formula from Larson [16] as shown by Eq. (2):

$$C_{future} = C_{measured} \times [0.2 + (G \times 0.8)] \tag{2}$$

The MOBILE 5a program was used to predict vehicle exhaust emission factors. The vehicle mean exhaust emission factors usually decrease at a faster rate than annual traffic volume increasing rate, because newer cars with better pollution-control devices are to replace older cars. Consequently, the projected 2006 traffic activities are used to simulate the "worse-case" scenario for the design lifespan of the alternatives. MOBILE 5a default values, such as the operating mode (percent cold and hot starts) and percent of diesel vehicles were used. A Reid Vapor Pressure (RVP) of 10 psi was considered representative. The projected 2006 emissions had been used as inputs to the model for prediction of future exhaust emission factors.

Traffic emission factors during free-flow and idling phases are determined using MOBILE 5a outputs, and the projected peak hour traffic and vehicle categories. Vehicles are grouped into three (3) categories; Light Duty Vehicles (LDV), Light Duty Trucks (LDT) and Heavy Duty Trucks (HDT). LDT included all vehicles having two axles and six wheels and generally having a gross weight greater than 44 000 newtons, but less than 116 000 newtons. HDT included all vehicles having three or more axles, generally having a gross vehicular weight greater than 116 000 newtons. In this study, composite emission factors for free-flow segments of Mabel Signalized Intersection were between 17.90 and 20.16 g/miles, while the calculated idle emission factors ranged from 301.24 to 314.32 g/h.

3. Results and Discussion

3.1. Meteorological outputs

A set of meteorological conditions for Kuching City over a period of 10 years (1995-2004) was obtained from Kuching Airport Meteorological Station. The meteorological data demonstrated are to be normally distributed, and thus are warranted for application in Win Plot View. The mean wind velocity was observed to be 1.12 m/s with dominant wind direction from S69˚W (Fig. 2). Atmospheric stabilization class was generally based on the mean velocity, and in this study, Class B (moderate not stable) was used as input to CAL3QHC.

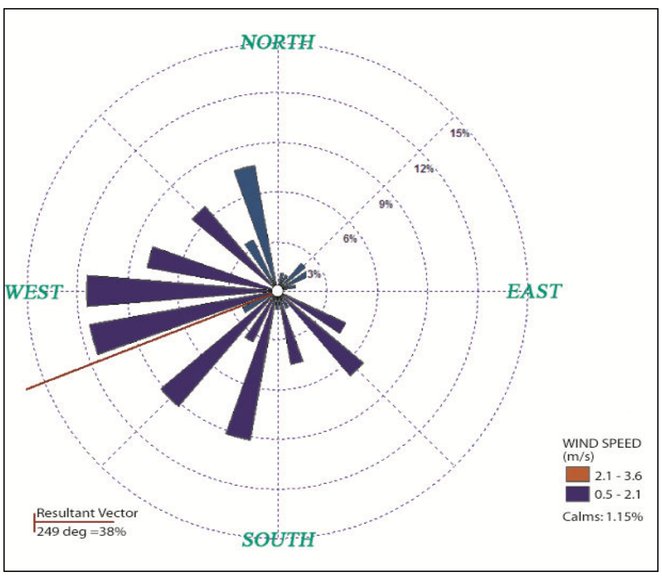

Fig. 2. Wind Direction for Kuching City from year 1995-2004. (Wind Rose Generated by Running Win Plot View).

3.2. Simulated ground-level CO concentrations (1-h TWA) for year 2006

Micro-scale CO dispersion modeling using CAL3QHC was carried out at Mabel Signalized Intersection during peak hours, namely morning (07:00-09:00) and late afternoon (17:00-19:00). One of the CO hot-spots was found at KchR6 (101 Commercial Park) located southeast of the intersection, showed to result in a maximum CO concentration (1-h TWA) of 18.3 ppm and 18.6 ppm during A.M. peak and P.M. peak, respectively. Nearby residential areas such as KchR1 (Petronas Petrol Station), KchR4 (Phoning Park), KchR5 (Everbright Jaya), KchR10 (Mabel Garden) and KchR11 (Kenny Hills Park), the simulated CO concentrations were observed to be in the range of 5.9–9.6 ppm during peak hours. KchR7 (S.M.K D.P.H.A. Gapoh Stampin), Perodua Showroom (KchR8) and KchR9 (Stampin East Garden) were found to have the lowest 1-h averaging ground-level CO concentrations during the peak hours. Based on the data of discrete receptors, KchR3 (Kpg. Tabuan Larang) and KchR2 (SKH Sdn. Bhd.) were found to experience relatively higher CO levels, which recorded 18.0 ppm and 13.6 ppm, respectively during A.M. peak hours; and 18.5 ppm and 14.3 ppm, respectively during P.M. peak hours (Fig. 3).

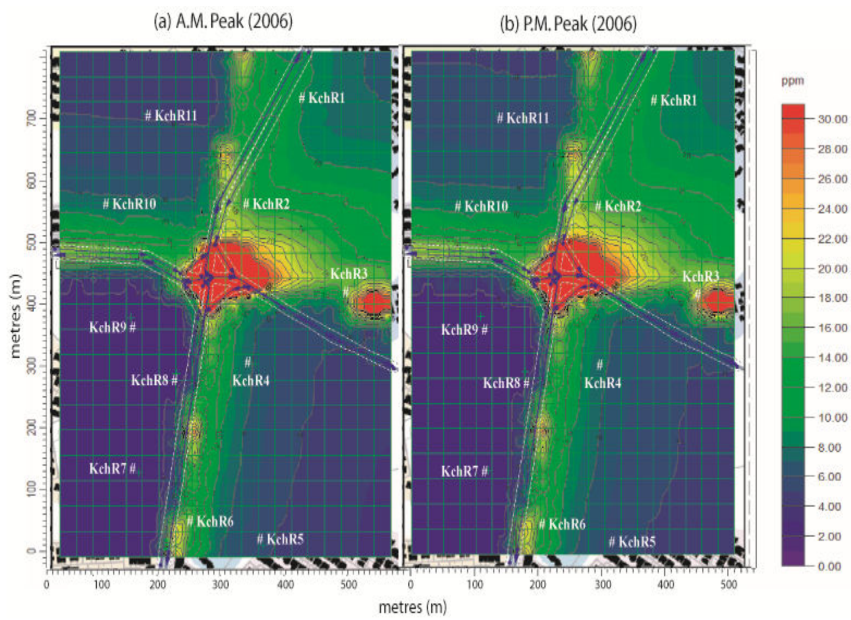

Fig. 3. Simulated 1-h Average CO Concentrations (ppm) during (a) A.M. and (b) P.M. Peak in Year 2006.

3.3. Comparison with field monitoring data

Evaluation of the performance of an air quality model would generally focus on the assessment on the accuracy of model simulated values as compared to observed values [18, 19]. In this study, data evaluations were performed quantitatively and statistically using the data obtained from the field measurements, and the results indicated that predicted CO simulated by micro-scale dispersion model correlated well with the observed CO values. The fractional bias screening test was selected as a basic measure of performance in this evaluation [18].

A comparison between measured and simulated 1-h TWA CO values during A.M. and P.M. peaks showed that the simulated values were slightly higher than the measured values [20]. The fractional bias (FB) of predicted CO concentrations was found to be close to zero for both A.M and P.M. peaks, indicating that measured and simulated results were relatively bias free (Table 2).

There was a strong correlation between the measured and simulated CO concentrations, with Linear Correlation of R^2 = 0.997 (p<0.05) for both A.M. and P.M. peaks (Fig. 4). Thus, a strong correlation between observed and predicted CO concentrations justified the application of the model to forecast future CO levels in the vicinity of intersection.

Table 2. Measured vs. Simulated 1-h TWA CO Values during A.M. and P.M. Peaks at Mabel Signalized Intersection.

Discrete Receptors/Hot-spots	A.M. Peak Hour			P.M. Peak Hour		
	Measured (ppm)	Simulated (ppm)	FB	Measured (ppm)	Simulated (ppm)	FB
KchR1 (Petronas Petrol Station)	8.9	9.6	0.08	9.1	10.3	0.12
KchR2 (SKH Sdn. Bhd.)	12.8	13.6	0.06	12.5	14.3	0.13
KchR3 (Kpg. Tabuan Larang)	15.6	18	0.14	15.8	18.5	0.16
KchR4 (Phoning Park)	7.2	7.8	0.08	7.5	8.2	0.09
KchR5 (Everbright Jaya)	6.2	6.1	-0.02	5.8	6.6	0.13
KchR6 (101 Commercial Park)	15.9	18.3	0.14	16.2	18.6	0.14
KchR7 (S.M.K. Stampin)	3.6	3.1	-0.15	3.6	3.6	0.00
KchR8 (Perodua Showroom)	3.5	3.1	-0.12	4	3.6	-0.11
KchR9 (Stampin East Garden)	3.6	3.1	-0.15	3.9	3.6	-0.08
KchR10 (Mabel Garden)	7.5	8.2	0.09	7.5	8.7	0.15
KchR11 (Kenny Hills Park)	5.6	5.9	0.05	5.6	6.4	0.13
***Fractional Bias**			0.02			0.08

**.Fractional Bias (FB) Screening Test:-*

$$FB = 2\frac{(\overline{C}_p - \overline{C}_m)}{(\overline{C}_p + \overline{C}_m)}$$

where $\overline{C}_m$ and $\overline{C}_p$ refer to the averages of the concentrations measured and simulated highest 25 values."The FB was selected as a basic measure of performance in this evaluation because it has two desirable features. First, the fractional bias is symmetrical and bounded; values for the fractional bias range between -2.0 (extreme under-prediction) to +2.0 (extreme over-prediction). Second, the fractional bias is a dimensionless number, which is convenient for comparing the results from studies involving different concentration levels, or even different chemical parameters. Values of the FB that are equal to -0.67 are equivalent to under-prediction by a factor of two, while values of the FB that are equal to +0.67 are equivalent to over-prediction by a factor of two. Model predictions with a fractional bias of 0 (zero) are relatively free from bias."

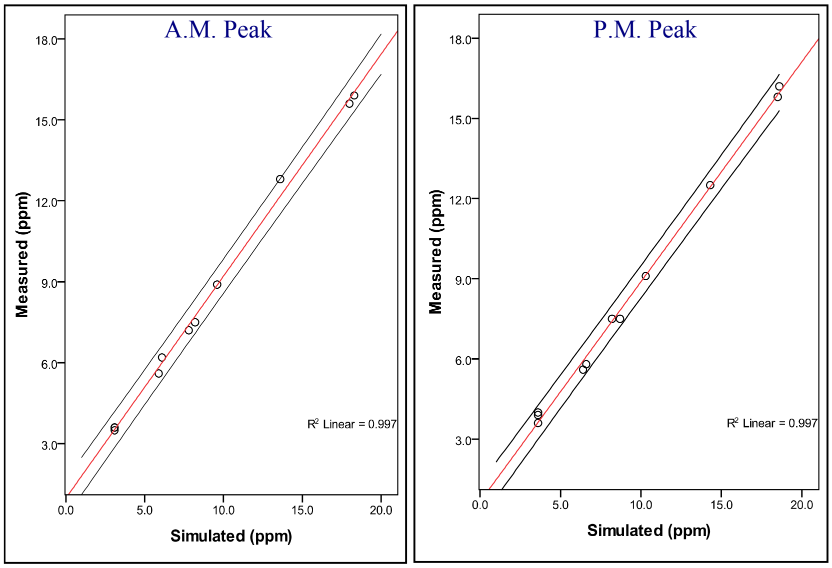

Fig. 4. Measured vs. Simulated 1-h TWA CO Values during A.M. and P.M. Peaks at Mabel Signalized Intersection.

3.4. Simulated ground-level CO concentrations (1-h TWA) for year 2014

Isopleths of 1-h averaged CO concentrations were simulated using CAL3QHC dispersion model for A.M. and P.M. peaks for year 2014 (Fig. 5). The simulated CO levels for KchR6 (101 Commercial Park) during A.M. peak (20.4 ppm) and P.M. peak (20.8 ppm) in year 2014 were identified as one of the highest, as compared with other discrete receptors or hot-spots located in the vicinity of Mabel Signalized Intersection. Simulated CO values at discrete receptor KchR3 at Kpg. Tabuan Larang was 20.1 ppm (second highest) during A.M. peak and 20.7 ppm during P.M. peak. The simulated CO concentrations for the rest of the discrete receptors were in the range of 5.2 –16.6 ppm during peak hours (Table 3).

The CAL3QHC simulated results showed that pollutant was dispersed dominantly to the northeast direction, which corresponded to approximately S69°W as dominant wind direction. Analysis on the emission source strengths showed that CO levels were relatively higher among discrete receptors located close to the signalized intersection, with respect to locations on the east of the roadway such as KchR1, KchR2, KchR3 and KchR6. Discrete receptor KchR6 (101 Commercial Park) had the highest CO concentration (1-h TWA) which might be due to long queuing motor vehicles idling alongside Tun Jugah Road during A.M. and P.M. peak hours.

The “point” (400 m east, 50 m south) of the intersection marks the ending of a 2-lane roadway, and the beginning of a 5-lane roadway on Song Road (heading west) with two right-turn lanes to Kuching By-Pass, one left-turn lane to Tun Jugah Road, and two lanes heading west to Laksamana Cheng Ho Road (Figs. 1, 3 and 5).

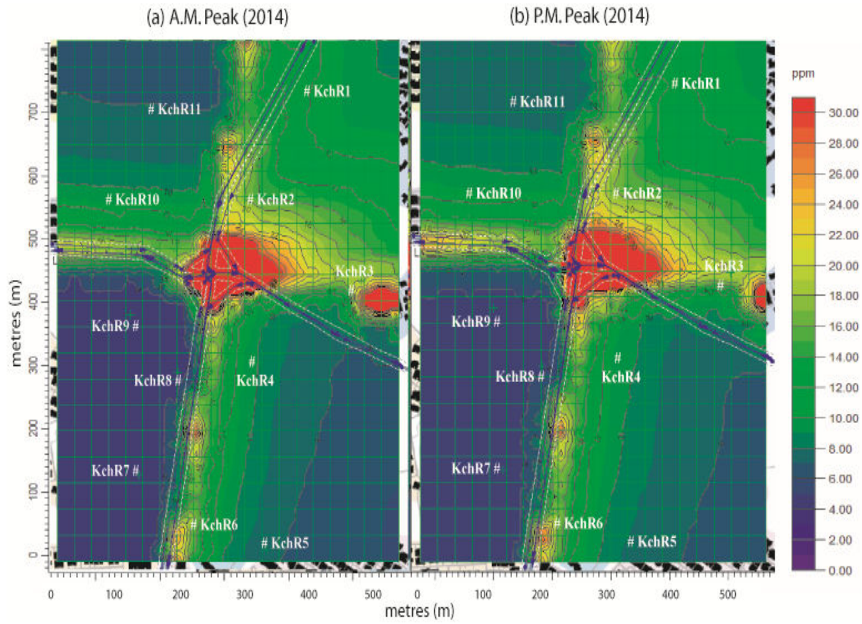

Fig. 5. Simulated 1-hr TWA CO Levels (ppm) for Year 2014 at Mabel Signalized Intersection during (a) A.M. Peak and (b) P.M. Peak.

Table 3. Simulated CO Levels at Mabel Signalized Intersection for Year 2014.

Research Area: Mabel Signalized Intersection, Kuching			**Forecasting Year: 2014**	
Pollutant	**Discrete Receptors/ Hot-spots**	**1 h TWA Concentration (ppm)**		**MAAQG Limit (ppm)**
		A.M. Peak	**P.M. Peak**	
Carbon Monoxide (CO)	KchR1 (Petronas Petrol Station)	11.8	12.6	< 30
	KchR2 (SKH Sdn. Bhd.)	15.9	16.6	
	KchR3 (Kpg. Tabuan Larang)	20.1	20.7	
	KchR4 (Phoning Park)	9.9	10.4	
	KchR5 (Everbright Jaya)	8.2	8.7	
	KchR6 (101 Commercial Park)	20.4	20.8	
	KchR7 (S.M.K. D.P.H.A.G.S)	5.2	5.7	
	KchR8 (Perodua Showroom)	5.2	5.7	
	KchR9 (Stampin East Garden)	5.2	5.7	
	KchR10 (Mabel Garden)	10.3	10.8	
	KchR11 (Kenny Hills Park)	8.0	8.5	

It was observed that nearly all motor vehicles heading west, upon reaching this "point" would accelerate notably during green light, which resulted in significant increase in CO emissions. It is noteworthy that southwest (S69°W) is the dominant wind direction, and KchR3 was located approximately 50 m northeast of the "point" (downwind of dominant wind direction). Thus, second highest maximum CO concentration (1-h TWA) recorded at KchR3 was attributed to sudden accelerating vehicles and its location downwind of dominant wind direction. The concentration levels for most of the others discrete receptors were below 15 ppm. Based on the simulated results, CO levels at Mabel Signalized Intersection were still acceptable and remained below the Malaysian Ambient Air Quality Guideline of 30 ppm (1-h TWA). Relatively higher CO levels at the intersection mainly originated from motor vehicle emissions. Strong positive relationships were observed between the measured CO levels (1-h TWA) and hourly vehicles volume at all monitoring sites with R2 ranging from 0.992 to 1.000. This indicated that motor vehicles contributed most of the CO emission. There are similar observations reported by researchers elsewhere with respect to predominant CO emission from motor vehicles [21].

Traffic flow condition could have also attributed to relatively higher CO levels at the intersection. At Mabel Signalized Intersection, highest number of motor vehicles had been observed during the morning and evening peak hours. This condition could have significantly elevated CO concentrations [6, 22]. It was also observed that the 120-second signal cycle at the intersection was comparatively longer than any other intersection in Kuching City. This condition allowed vehicles from various directions to remain idle for a longer time, and thus more CO being emitted. Motor vehicles with running engine in an idle position had shown to emit more CO than in free flow conditions [23]. Highest CO levels at busiest intersections could have been due to the impact of elevated exhaust plumes from slowly moving vehicles as observed in another study by [7]. The traffic occupancy effect that has been related to the effect of vehicle induced air turbulence in the "mixing zone" could also be responsible for CO variations at monitoring sites. Among other factors that could affect the variations of CO concentration, but have not been investigated in this study are the type of fuel used [24], age of the motor vehicles, local meteorological conditions [25], and existence of nearby high-rise buildings [26].

4. Conclusions

The simulated maximum 1-h (TWA) concentrations of CO during A.M. and P.M. peak hours at Mabel Signalized Intersection were in the range of 3.1–18.6 ppm for year 2006, and predicted to be between 5.2–20.8 ppm in year 2014. However, these values are still well below the Malaysian Ambient Air Quality Guideline of 30 ppm (1-h TWA). Current study showed that motor vehicles and traffic flow conditions were among the main factors for elevated CO levels, though insignificant. However, discrete receptors located close to the signalized intersection would experience marginally higher CO levels in the long-term.

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References

1. Faiz, A. (1993). Automotive emissions in developing countries-relative implications for global warming, acidification and urban air quality. *Transportation Research A.*: *Policy and Practice*, 27(3), 167-186.
2. Kho, F.W.L.; Law, P.L.; Ibrahim, S.H.; and Sentian, J. (2007). Carbon monoxide levels along roadway. *International Journal of Environmental Science and Technology*, 4(1), 27-34.
3. Mukherjee, P.; and Viswanathan, S. (2001). Carbon monoxide modeling from transportation sources. *Chemosphere*, 45(6-7), 1071-1083.
4. Chan, L.Y.; Lau, W.L.; Zou, S.C.; Cao, Z.X.; and Lai, S.C. (2002). Exposure level of carbon monoxide and respirable suspended particulate in public transportation modes while commuting in urban area of Guangzhou, China. *Atmospheric Environment*, 36(38), 5831-5840.
5. Colvile, R.N.; Hutchinson, E.J.; Mindel, J.S.; and Warren, R.F. (2001). The transport sector as a source of air pollution. *Atmospheric Environment*, 35(9), 1537-1565.
6. Claggett, M.; Shrock, J.; and Noll, K.E. (1981). Carbon monoxide near an urban intersection. *Atmospheric Environment*, 15(9), 1633-1642.
7. Hasnah, H.; Singh, P.; Gribben, R.J.; Srivastava, L.M.; Radojevic, M.; and Latif, A. (2000). Application of a line source air quality model to the study of traffic carbon monoxide in Brunei Darussalam. *ASEAN Journal on Science and Technology for Development*, 17, 59-76.
8. Schifter, I.; Diaz, L.; Vera, M.; Guzman, E.; and Lopez-Sallinas, E. (2003). Impact of sulfur-gasoline on motor vehicle emissions in the metropolitan area in Mexico City. *Fuel*, 82(13), 1605-1612.
9. Bogo, H.; Negri, R.M.; San Roman, E. (1999). Continuous measurement of gaseous pollutants in Buenos Aires city. *Atmospheric Environment*, 33(16), 2587-2598.
10. Moseholm, L.; Silva, J.; and Larson, T. (1996). Forecasting carbon monoxide concentrations near sheltered intersection using video traffic surveillance and neural networks. *Transportation Research Part D*: *Transport and Environment*, 1(1), 15-28.
11. Comrie, A.C.; and Diem, J.E. (1999). Climatology and forecast modeling of ambient carbon monoxide in Phoenix Arizona. *Atmospheric Environment*, 33(30), 5023-5036.
12. Law, P.L.; Lioy, P.J.; Zelenka, M.P.; Huber, A.H.; and McCurdy, T.R. (1997). Evaluation of a probabilistic exposure model applied to carbon monoxide (pNEM/CO) using Denver personal exposure monitoring data. *Journal of the Air and Waste Management Association,* 47(3), 491-500.
13. James, H.B. (2002). *Introduction to Transportation Engineering*. McGraw-Hill Co., 385-405.
14. Sharma, P.; and Khare, M.; and Chakrabarti S.P. (1999). Application of extreme value theory for predicting violations of air quality standards for an urban road intersection. *Transportation Research Part D*: *Transport and Environment*, 4(3), 201-216.
15. Trinity Consultants Incorporated (1993). *CAL3QHC User's Manual*. North Carolina: Research Triangle Park, NC: United States of America.
16. Larson, T.; Moseholm, L.; Slater, D.; and Cain, C. (1996). Local Background levels of carbon monoxide in an area. *Transportation Research A.*: *Policy and Practice*, 30(6), 399-413.

17. USTRB (2000). *Highway Capacity Manual* (4^{th} ed.), Washington: United States Transportation Research Board, United States of America.
18. USEPA (1992). *Protocol for Determining the Best Performing Model.* North Carolina: Research Triangle Park, NC: United States of America.
19. Onursal, B.; and Gautam, S. (1997). Vehicular air pollution: experiences from seven Latin American urban centers. *World Bank Technical Paper No: 373*, The International Bank of Reconstruction and Development. Washington DC, USA.
20. Kho, F.W.L. (2008). *Assessment of carbon monoxide levels at signalized intersection and roadway*. MEng Thesis, University Malaysia Sarawak, Kota Samarahan, Malaysia.
21. Borrego, C.; Tchepel, O.; Costa, A.M.; Amorium, J.H.; and Miranda, A.I. (2003). Emission and dispersion modeling of Lisbon air quality at local scale. *Atmospheric Environment*, 37(37), 5197-5205.
22. Sivacoumar, R.; and Thanasekaran, K. (1999). Line source model for vehicular pollution prediction near roadways and model evaluation through statistical analysis. *Environmental Pollution*, 104(3), 389-395.
23. Fenger, J. (1999). Urban air quality. *Atmospheric Environment*, 33(29), 4877-4900.
24. Chan, L.Y.; and Liu, Y.M. (2001). Carbon monoxide levels in popular passenger commuting modes traversing major commuting routes in Hong Kong. *Atmospheric Environment*, 35(15), 2637-2646.
25. Luria, M.; Weisinger, R.; and Peleg, M. (1990). CO and NO_x levels at the center of city roads in Jerusalem. *Atmospheric Environment*, *Part B*, 24(1), 93-99.
26. Zhou, H.; and Sperling, D. (2001). Traffic emission pollution sampling and analysis on urban streets with high-rising buildings. *Transportation Research Part D*: *Transport and Environment*, 6(4), 269-281.