ORIGINAL ARTICLE

Prediction of CO concentrations from road traffic at signalized intersections using CAL3QHC model: the Khon Kaen case study

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Abstract

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Based on the US EPA air pollution model, CAL3QHC version 2.0 was applied to predict carbon monoxide (CO) concentrations from road traffic at three signalized intersections in Khon Kaen province. Four data groups required by the model, namely site parameters, traffic parameters, meteorological parameters and emission parameters were collected at each intersection and have been used as the inputs to the model. The prediction results were compared to the measurement. The results showed that the predicted CO concentration variations corresponding mostly to the measurement except at some hours when there was not good agreement due to an extreme upwind location of receptor, low wind speed, raining period, other out-sources of CO concentration such as another near intersection and parking lot. However, this study

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shows that the CAL3QHC model can be applied to predict CO concentration in the environmental condition of Thailand quite well. Moreover, the model might be used as a tool for assessing traffic air pollution at roadway intersection as well as for air quality management.

Key words : carbon monoxide, air pollution model, CAL3QHC, road traffic, signalized intersection

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บทคัดย่อ

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การทำนายค่าความเข้มข้นก๊าซคาร์บอนมอนอกไซด์จากการจราจรบริเวณทางแยกสัญญาณไฟจราจรโดยใช้แบบจำลอง CAL3QHC: กรณีศึกษาขอนแก่น

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แบบจำลองมลพิษทางอากาศของ Environmental Protection Agency (EPA) ประเทศสหรัฐอเมริกาที่มีชื่อว่า CAL3QHC version 2.0 ถูกนำมาประยุกต์ใช้เพื่อทำนายค่าความเข้มข้นก๊าซคาร์บอนมอนอกไซด์ (Carbon Monoxide, CO) จากการจราจรบริเวณทางแยกในพื้นที่จังหวัดขอนแก่นจำนวน 3 ทางแยก ในการศึกษาได้มีการเก็บรวบรวมข้อมูลที่ต้องการสำหรับแบบจำลอง ซึ่งได้แก่ ข้อมูลของทางแยก ข้อมูลด้านการจราจร ข้อมูลอุตุนิยมวิทยา และข้อมูลการแพร่ออกมาของมลพิษอากาศในบริเวณแต่ละทางแยก หลังจากนั้นข้อมูลดังกล่าวจะใช้เป็นข้อมูลนำเข้าสำหรับแบบจำลองมลพิษทางอากาศ และผลจากการทำนายจะถูกเปรียบเทียบกับค่าที่ตรวจวัดได้จริง ผลจากการทำนาย พบว่าการเปลี่ยนแปลงของค่าความเข้มข้นก๊าซคาร์บอนมอนอกไซด์ที่ได้จากการทำนายในแต่ละชั่วโมงโดยส่วนใหญ่จะมีความสอดคล้องกับค่าความเข้มข้นก๊าซคาร์บอนมอนอกไซด์ที่ได้จากการตรวจวัด ยกเว้นในบางชั่วโมงที่ผลการทำนายมีค่าไม่สัมพันธ์กันกับผลที่ตรวจวัดได้ เนื่องมาจากหลายสาเหตุ ได้แก่ ตำแหน่งของจุดตรวจรับมลพิษอากาศที่อยู่เหนือลม ความเร็วลมต่ำ ช่วงเวลาที่มีฝนตก และมีแหล่งกำเนิดก๊าซคาร์บอนมอนอกไซด์อื่นอยู่ใกล้ เช่น ทางแยกและที่จอดรถ แต่อย่างไรก็ตาม การศึกษานี้ได้แสดงให้เห็นว่าแบบจำลอง CAL3QHC สามารถที่จะนำมาประยุกต์ใช้เพื่อทำนายค่าความเข้มข้นก๊าซคาร์บอนมอนอกไซด์ในสภาพแวดล้อมของประเทศไทยได้ค่อนข้างดี นอกจากนั้น แบบจำลองนี้อาจสามารถนำไปใช้เป็นเครื่องมือในการประเมินผลกระทบมลพิษทางอากาศจากการจราจรบริเวณทางแยกและอาจนำไปใช้สำหรับการจัดการคุณภาพอากาศได้ดีเช่นเดียวกัน

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Air pollution is widely recognized as one of principal pollutants in most of major cities. In urban areas, traffic congestion on road networks produces air pollutants since most vehicles use internal combustion engines which consume fuel that emits various types of toxic gases such as carbon monoxide (CO), nitrogen oxide (NOx), hydrocarbons (HC) and particulate matter (PM). Generally, air pollution concentrations near road junctions are higher than at roadway links due to vehicles spending longer periods of time near junctions, in driving modes (i.e., deceleration, queuing and acceleration) which generate a lot of pollutants. Therefore, air pollution at roadway intersection is of particular importance and should be studied. The emission rates of pollutants in different modes and speeds of each vehicle type are normally used to estimate pollutant emissions from motor vehicles and the mathematical model such as Gaussian dispersion model can be used to predict the dispersion of pollutants. This paper describes the methodology of air pollution concentration prediction from motor vehicles at signalized intersections and the results of comparison between the CO concentrations from the prediction and corresponding measurement.

Materials and Methods

Model Description

CAL3QHC is a microcomputer-based model to predict carbon monoxide (CO) or other inert pollutant concentrations from motor vehicles at roadway intersections. The model includes CALINE-3 line source dispersion model and a traffic algorithm for estimating vehicular queue lengths at signalized intersections (EPA, 1995). CALINE-3 is designed to predict air pollutant concentrations near highways and arterial streets due to emissions from motor vehicles operating under free flow conditions (Caltrans, 1979). However, it does not permit the direct estimation of the contribution of emissions from idling vehicles. CAL3QHC enhances CALINE-3 by incorporating methods for estimating queue lengths and the contribution of emissions from idling vehicles. The model permits the estimation of total air pollution concentrations from both moving and idling vehicles. It is a reliable tool for predicting concentrations of inert air pollutants near signalized intersections because idle emissions account for a significant portion of the total emission at an intersection. The model currently can predict air pollutant concentration from road traffic only at the intersection which is controlled by traffic signal. The theories and other details of the dispersion model and queuing algorithm are given in Caltrans (1979) and EPA (1995).

Sites Description

The municipal area of Khon Kaen city located in Northeastern part of Thailand was adopted as the study area. Then three intersections in the study area were selected as case studies. These intersections are the Sanambin School (SNB) intersection, Khon Kaen Hospital (KKH) intersection, and Siam Commercial Bank (SCB) intersection. The reasons of the selection of these intersections are as follows: (i) the SNB intersection is located near an ambient air monitoring station of Pollution Control Department (PCD) and this intersection also is surrounded by various sensitive areas such as primary schools, a vocational college, official residences, and so on; (ii) the KKH intersection is also surrounded by sensitive areas such as the Khon Kaen Hospital and many semi-commercial buildings; (iii) the SCB intersection is located in the central business district (CBD) area and is surrounded by the Siam Commercial Bank and also many semi-commercial buildings. The geographical location of these three intersections is presented in Figure 1. The lane configurations and adjacent land use characteristics of the intersections are described below.

The SNB intersection is a 4-leg signalized intersection of Prachasamosorn Road and Lungmuang Road. Figure 2 shows the configuration of the intersection. Prachasamosorn Road is a divided road with a raised median aligned in the East-West direction. The road consists of three lanes in each direction plus exclusive one right-turning lane on each approach. Lungmuang Road is an undivided two-way road nearly aligned along the North-South direction. Each direction consists of two lanes (one lane for left turn and another one for straight and right turn). This intersection is surrounded by two schools, a college and many governmental offices.

The KKH intersection is a 4-leg signalized intersection consisting of two intersecting roads, namely Srichan Road and Chatapadung Road, as shown in Figure 3. Srichan Road is a divided 8-lane road (four lanes in each direction) with a raised median, approximately aligned along the East-West direction with exclusive one right-turning lane on each approach. Chatapadung Road is a divided 4-lane road (two lanes in each direction) with a raised median, running along the North-South direction. The centerlines of the two roads are not coincident. This intersection is near the Khon Kaen Hospital and surrounded by semi-commercial buildings.

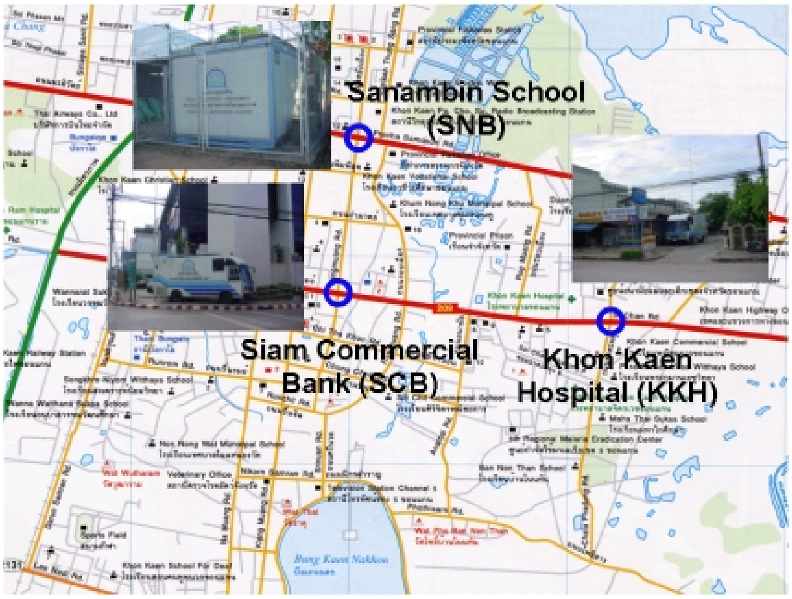

Figure 1. Location of the intersections and photos of air monitoring stations

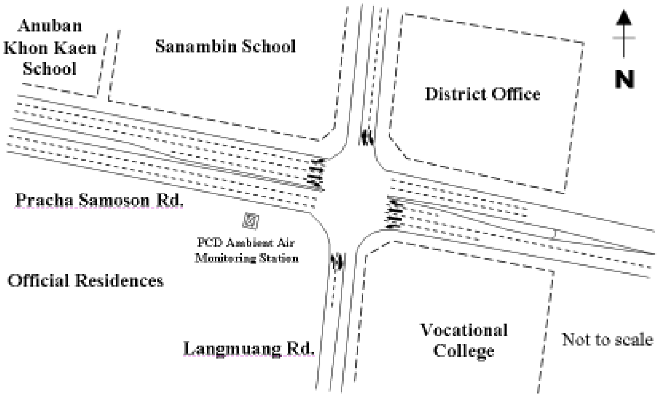

Figure 2. Lane configurations and land use characteristics of SNB intersection

The SCB intersection is a 4-leg signalized intersection consisting of two intersecting roads, namely Srichan Road and Lungmuang Road, as shown in Figure 4. Srichan Road is an undivided 4-lane (two lanes in each direction) road with exclusive one right-turning lane on each approach. The physical configuration of Lungmuang Road at this intersection is similar to the SNB intersection. This intersection is near the Siam Commercial Bank and surrounded by many semi-commercial buildings.

Data Collection and Acquisition

Data required for CAL3QHC model are divided into the 4 main parameters: site parameters, traffic parameters, meteorological parameters and emission parameters. Therefore, data collection and acquisition of the study were conducted following these parameter groups.

Site parameters

Site parameters are mainly related to geometric dimensions of intersection and a position of

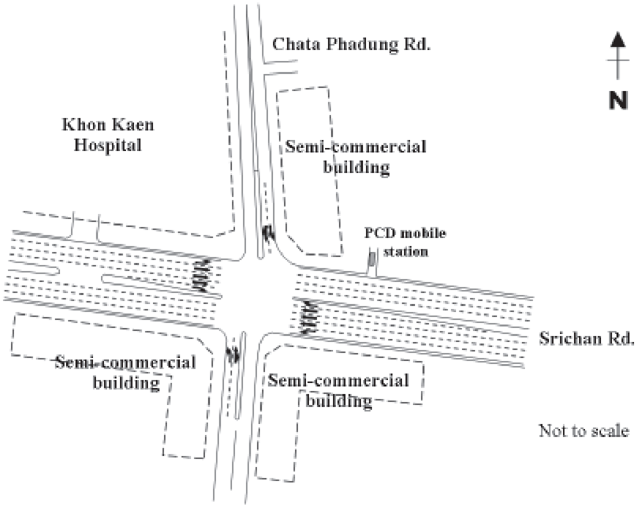

Figure 3. Lane configurations and land use characteristics of KKH intersection

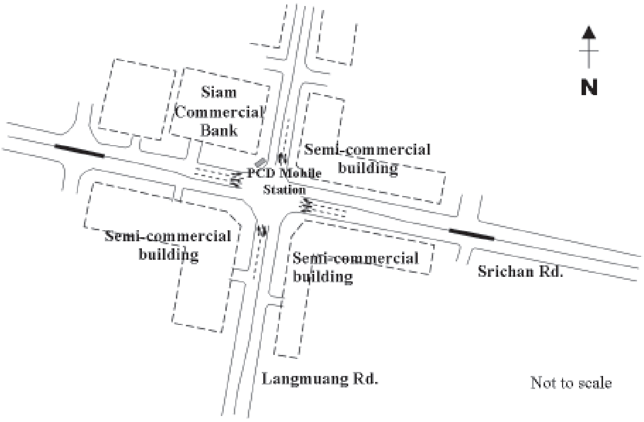

Figure 4. Lane configurations and land use characteristics of SCB intersection

each. The locations of each free flow and queue links must be determined. Traffic signal phases and geometric dimensions of each intersection such as lane configurations, roadway widths are needed to locate the position of each link. The position of all elements should be specified by using an X, Y, and Z coordinating system and are referred to the origin point that has a coordinate of (0, 0) at the center of the intersection.

In order to determine locations of each free flow link, each lane group that serves different directions and has different characteristics such as traffic volume, emission factor, width and height is separated. Each free flow link begins in the center of the intersection and is aligned with the respective approach either in the x- or the y-directions. It can be noted that exclusive right turn lanes are not counted for free flow links because the link length is very short and therefore can be neglected (Siriyong, 2001). It can be noted that free flow link alignments are located at a half width of each lane group. Link width of free flow link is defined as the width of traveled road plus 3 meters on each side to account for the dispersion of the plume generated by the wake of moving vehicles (EPA, 1995). These above mentioned are illustrated in

Figure 5.

Locations of queue links can be determined by separating each lane group, which is served by different red time phases and has different characteristics such as traffic volume, emission factor, width and height. A queue is defined as a straight segment, on which vehicles are idling for a specified period of time. The actual length of the queue is estimated by the program based on traffic volume and capacity of approach. No queue link is located at all departure approaches, since departure approaches are not affected by a traffic signal. It should be noted that exclusive right turn lanes are counted for a queue link because an idle emission has a substantial effect on the amount of emitted pollutant. All queue links cannot be omitted. Link width of any queue links is determined by the width of the traveled roadway. Three meters are not added on each side because vehicles are not moving and no wake is generated as illustrated in Figure 6.

Each link of both free flow and queue link at each intersection should be named for easy recognition as shown for all free flow and queue links of the SNB intersection as example in Figures 7-8, respectively. The location of the receptor,

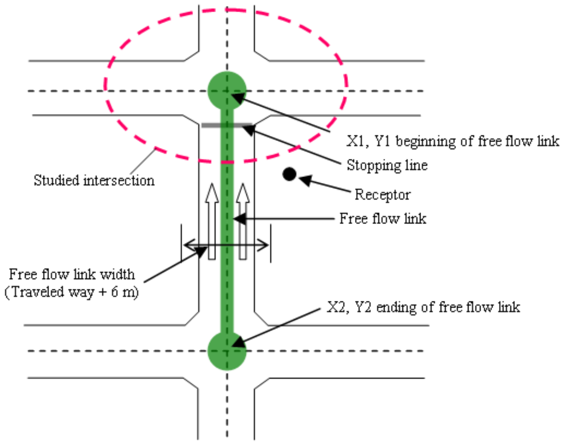

Figure 5. Location and physical elements of free flow link

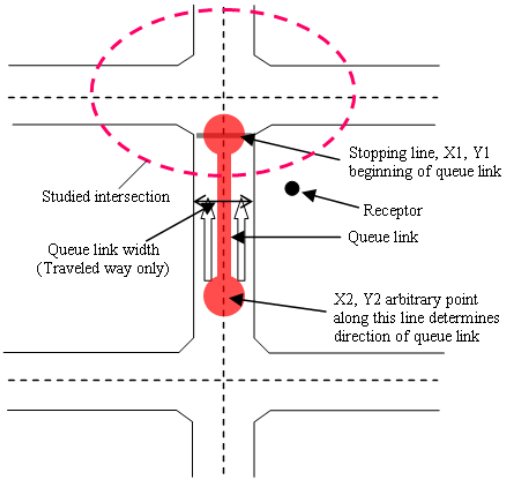

Figure 6. Location and physical elements of queue link

ambient air monitoring station of the Pollution Control Department (PCD) at each intersection is also required to be used in the calculation process of the CO concentration at such point.

Traffic parameters

Traffic volume of each lane group (free flow links and queue links) of each intersection was collected separately according to vehicle and engine-fueled types; Gasoline Vehicle (GV), Small Diesel Vehicle (SDV), Large Diesel Vehicle (LDV), and Motorcycle (MC). Data collection was conducted 3 days for each intersection. At the SNB intersection, traffic flows were collected on July 9, 2003 during 7:00-18:00 (11 hours) and January, 16-17, 2004 during 6:00-18:00 (12 hours per day). At KKH intersection and SCB intersection, traffic volumes were observed for three days during 6:00-18:00 (12 hours per day) at each intersection, on August 21-23, 2003 and August 28-30, 2003, respectively. Moreover, signal cycle length, red time, clearance lost time, saturation flow rate, signal type and arrival rate of each lane group were collected at the intersections.

Meteorological parameters

The Pollution Control Department (PCD) installed a permanent ambient air monitoring

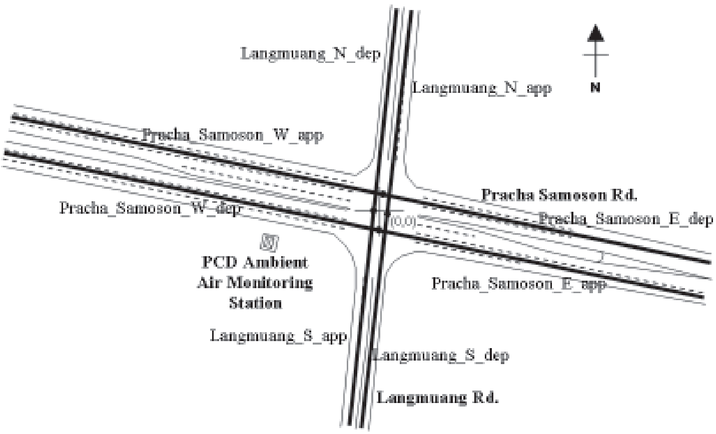

Figure 7. Each free flow link of the SNB intersection

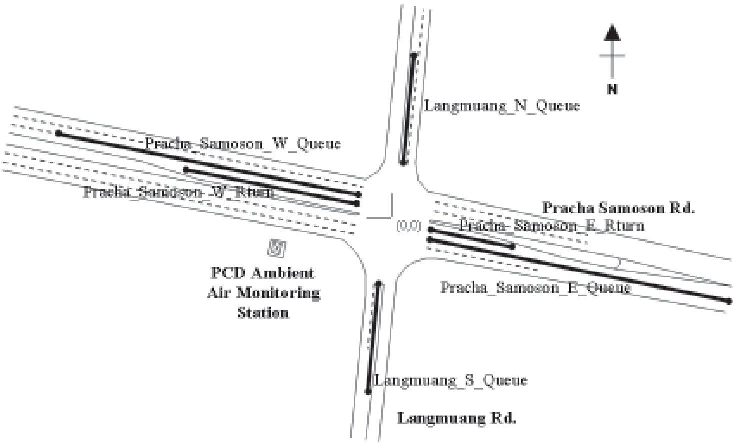

Figure 8. Each queue link of the SNB intersection

station in Khon Kaen municipality at the SNB intersection in 1996. Thus, the meteorological data and air pollution data of this site are available all the time. For other two intersections, PCD installed a mobile ambient air monitoring station near these intersections for measuring the meteorological data and CO concentrations. Main meteorological data such as wind speed, wind direction, and solar radiation were obtained from the equipment. Some other data were acquired by other methods such as observation at the sites, deriving from other parameters, statistical data, and the default recommendations, for example, the surface roughness coefficient can be observed at each site (EPA, 1995); the atmospheric stability class can be determined by the influence of solar radiation and wind speed (Colls, 2002); the background concentration at each site of each month of the data collection can be determined from the diurnal CO variation of that month (Colls, 2002); and the EPA recommendation, 1,000 meters mixing height was adopted because the data collection period of this study is in daytime (6:00-18:00) when the mixing height is normally high and this study is done on a microscale so that sensitivity to mixing height is significant only for extremely low value (much less than 100 m) (EPA, 1992). Moreover, rainfall of each hour was collected by the equipment and raining period at the sites also was noted by observers.

Emission parameters

Emission factors for both running and idling operations are required parameters for the application of the CAL3QHC model (EPA, 1995). Due to the lack of information regarding emission factors, the running emission factors derived from a recent study, the project of Improving Database of Air Pollution Sources and Evaluating Air Quality Impact in Chiang Mai municipality and surrounding area (CMM *et al.*, 2002), was employed. This use of emission factors applied for the Chiang Mai city to this Khon Kaen city case study is based on the assumption that the vehicle type, driver behavior, the inspection and maintenance programs, and other factors in Chiang Mai and Khon Kaen are relatively similar. Unfortunately, the idling emission rates are not available in Thailand, therefore the idling emission rates recommended by the Office of Mobile Sources, EPA (EPA, 1998) was adopted in this study. The composite emission of each lane group could be calculated by the weighting average method according to number of each vehicle type on each lane group (Siriyong, 2001).

Moreover, the actual CO concentration at each intersection of each collected hour also was collected for comparing to the predicted concentrations.

Input Data Preparation and Model Running

All required parameters of CAL3QHC were prepared in hourly data sets. All parameters of each hourly data set were arranged in CAL3QHC input file format (EPA, 1995), and then input made to the model. After model ran, the hourly CO concentration at each receptor could be obtained. The major routines of the CAL3QHC model and how they interact can be seen in Figure 9. A description of these routines and how each input parameter used in the model is provided in EPA (1995).

Results and Discussion

As collection at the SNB began at 7.00 a.m. on the first day, and the CAL3QHC cannot measure effectively when the wind speed is lower than 1 m/s, only 94 hourly data sets were used for calculating. The CO concentration during some hours could not be measured either because they coincided with the calibrating periods of the equipment, or because the CO concentration was lower than the detection limit of the equipment. As a result, only 88 hourly data sets could be used for comparison.

Results of the prediction at SNB Intersection

The data collection at this site was conducted on 9 July 2003, which was in the rainy season and on 16-17 January 2004, which was in the winter season.

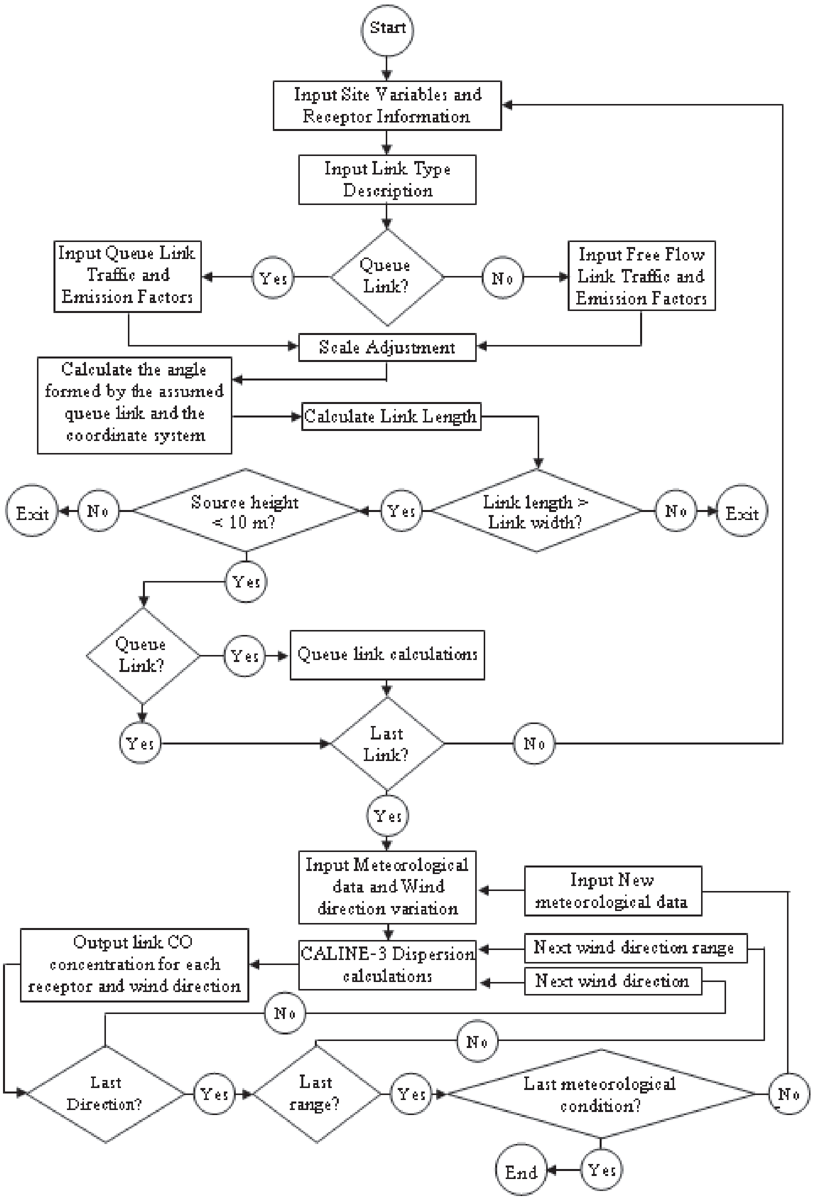

Figure 9. Flowchart for CAL3QHC routines (Source: EPA, 1995)

Results of the prediction on Wednesday, 9 July 2003

The data sets of 11 hours from 7.00-17.00 on 9 July 2003 were calculated. The predicted and measured CO concentrations are plotted and shown in Figure 10 (a). The trends of predicted and measured CO concentration are quite similar. The errors of prediction from 7.00-15.00 are not more than 0.2 ppm. The error at 16.00 and 17.00 is about 0.6 and 0.7 ppm respectively, due to the occurrence of an extreme upwind at 16.00, which affected the result until 17.00, and wind speed decreasing from 2.3 m/s at 15.00 to 1.3 m/s at 16.00.

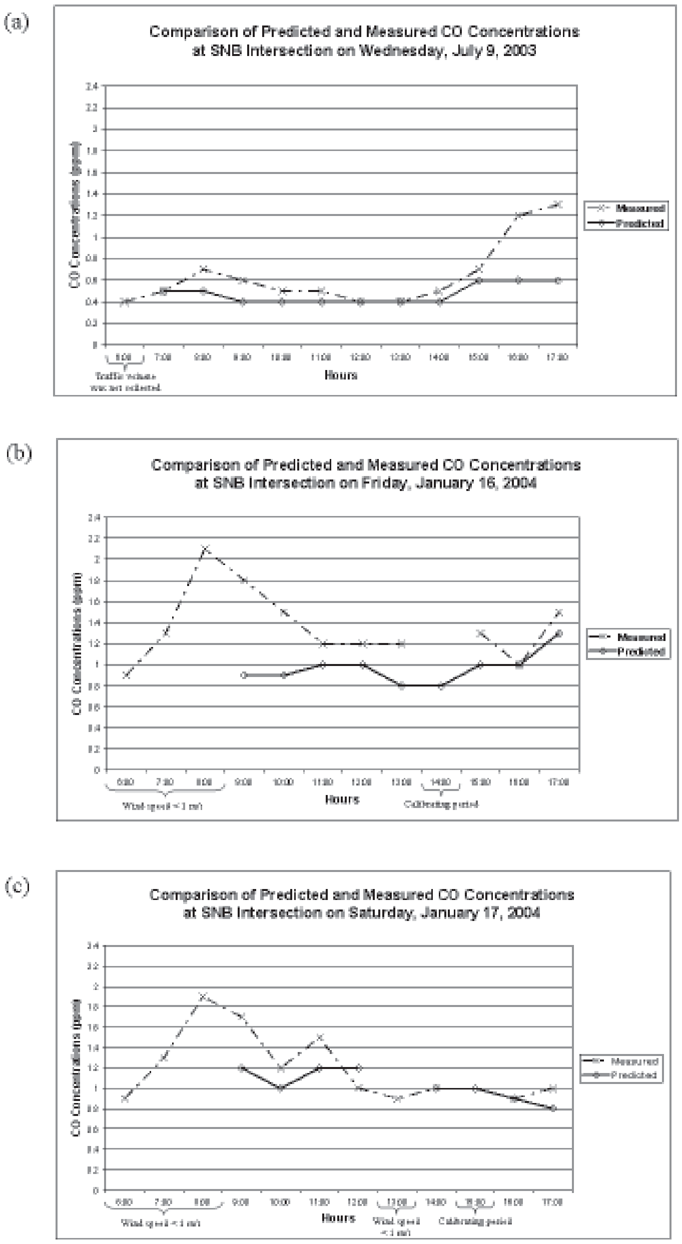

Figure 10. The variation of predicted and measured CO concentrations

Results of the prediction on Friday, 16 January 2004

The data sets of 9 hours from 9.00-17.00 on 16 January 2004 were calculated. The predicted and measured CO concentrations are plotted and shown in Figure 10 (b). The trends of predicted and measured CO concentration on this day are not quite similar. During 6.00-9.00, the wind speeds were lower than 1 m/s, therefore the CAL3QHC was not used, because it leads to low accuracy. The low wind speed also resulted in CO concentrations being accumulated as the differences of concentration at 9.00 and 10.00 are about 0.9 and 0.6 ppm respectively. The CO concentration at 14.00 was not measured because this was the calibrating period of the equipment.

Results of the prediction on Saturday, 17 January 2004

The data sets of 8 hours from 9.00-12.00 and 14.00-17.00 on 17 January 2004 were calculated. The predicted and measured CO concentrations are plotted and shown in Figure 10 (c). The trends of predicted and measured CO concentration are quite similar. The errors of prediction are not more than 0.5 ppm. During 6.00-8.00 and at 13.00, the wind speeds were lower than 1 m/s therefore these hourly CO concentrations were not calculated. In addition, 15.00 was in the calibrating period of the equipment, therefore there was no observed CO concentration.

Results of the prediction at KKH Intersection

The data collection of this site was conducted during 21-23 August 2003, which was in the rainy season.

Results of the prediction on Thursday, 21 August 2003

The data sets of 12 hour from 6.00-17.00 on 21 August 2003 were calculated. The predicted and measured CO concentrations are plotted and shown in Figure 11 (a). The trends of predicted and measured CO concentration are similar. The errors of prediction are not more than 0.4 ppm.

Results of the prediction on Friday, 22 August 2003

The data sets of 11 hours from 6.00-16.00 on 21 August 2003 were calculated. The predicted and measured CO concentrations are plotted and shown in Figure 11 (b). The trends of predicted and measured CO concentration are similar. The errors of prediction from 6.00-12.00 are not more than 0.1 ppm. The error at 13.00 and 14.00 is about 0.5 and 0.3 ppm, respectively, and due to rain from 13.00-16.00, the observed CO concentrations were lower than the predictions. Moreover, during 15.00-16.00 the observed CO concentrations were very low, and could not be detected by the equipment.

Results of the prediction on Saturday, 23 August 2003

The data sets of 12 hours from 6.00-17.00 on 23 August 2003 were calculated. The predicted and measured CO concentrations are plotted and shown in Figure 11 (c). The trends of predicted and measured CO concentration are not quite similar because it was raining almost all of the day time with the maximum error of prediction of about 0.7 ppm at 8.00.

Results of the prediction at SCB Intersection

The data collection of this site was conducted from 6.00-18.00 during 28-30 August 2003, which was in the rainy season.

Results of the prediction on Thursday, 28 August 2003

The data sets of 12 hours from 6.00-17.00 on 25 August 2003 were calculated. The predicted and measured CO concentrations are plotted and shown in Figure 12 (a). The trends of predicted and measured CO concentrations are similar. The predicted CO concentrations on this day are lower than the measurements with the errors about 0.4-0.9 ppm, due to the SCB intersection being located in the downtown, where traffic volume is very high in the adjacent area and, moreover, there is an underground parking lot close to the measurement station. Thus, such other sources of CO are significant but they were not considered as additional background concentration input to the model. In addition, the observation of CO concentration was not performed at 6:00 because of the calibrating period for the equipment.

Results of the prediction on Friday, 29 August 2003

According to the calibrating period from 7.00-8.00 and the wind speed during 7.00-8.00 and 10.00-11.00 being lower than 1 m/s, only 8 hourly data sets were calculated. The predicted and measured CO concentrations are plotted and shown in Figure 12 (b). The trends of predicted and

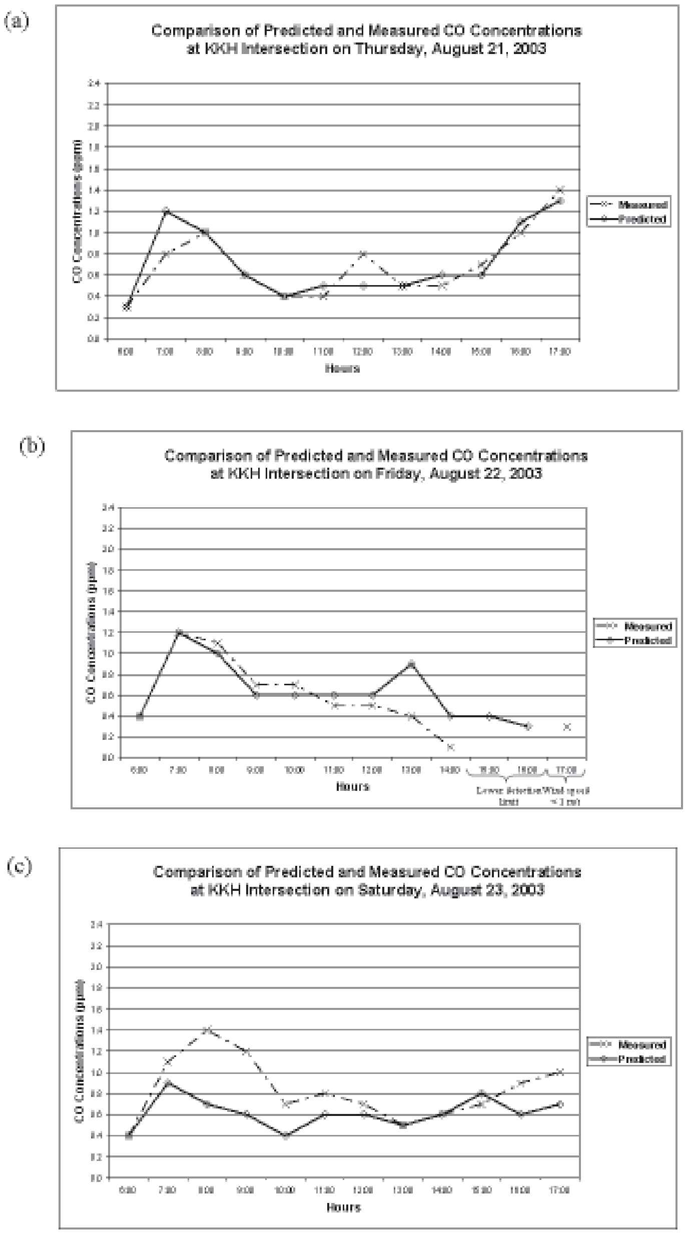

Figure 11. The variation of predicted and measured CO concentrations at KKH intersection

measured CO concentrations are similar. The errors are between 0.7-1.1 ppm, the measurement of CO is high because of the heavy traffic of another intersection and exhaust from the parking lot of the bank as described. The measured CO concentration at 8.00 is highest due to the low wind speed that resulted in the accumulation of CO concentration.

Results of the prediction on Saturday, 30 August 2003

Due to the calibration of equipment at 8.00 and the wind speed less than 1 m/s at 12.00, only 11 hourly data sets were calculated. The predicted

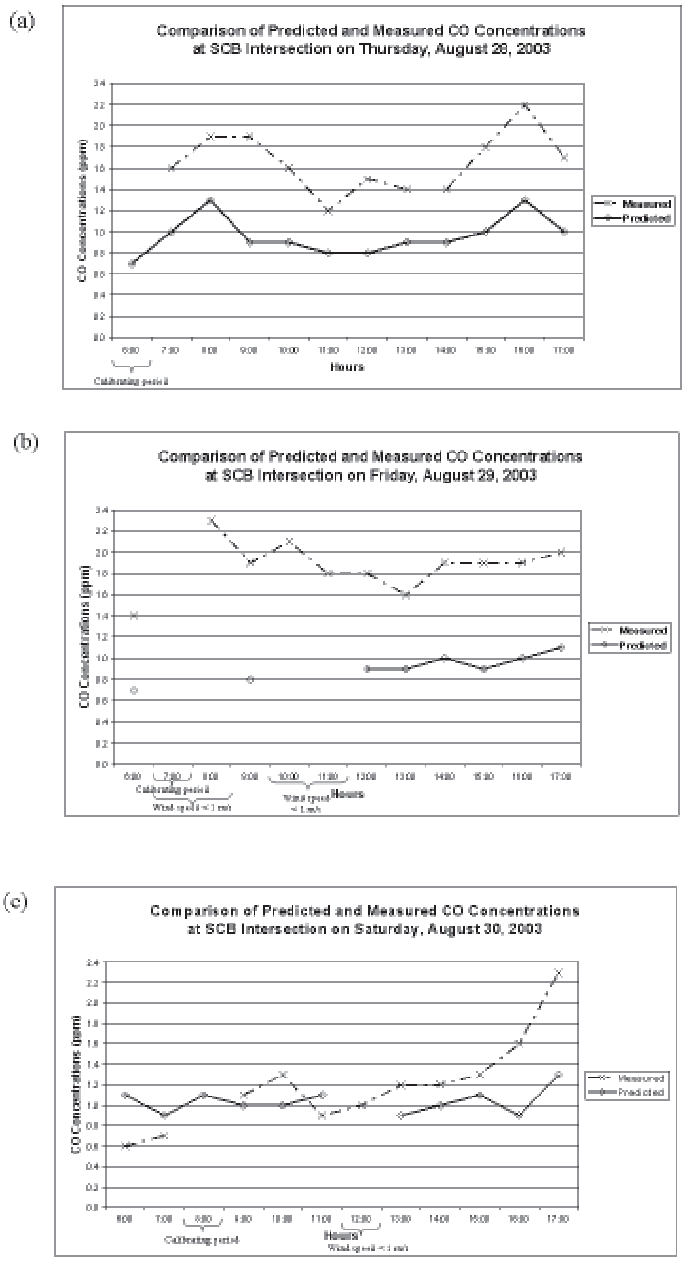

Figure 12. The variation of predicted and measured CO concentrations at SCB intersection

and measured CO concentrations are plotted and shown in Figure 12 (c). The trends of predicted and measured CO concentrations are quite similar. The errors of prediction are not more than 0.5 ppm, because this day was Saturday (weekend day), when the parking lot of the bank was closed, so the measured CO concentration was not disturbed by the exhaust from vehicles in the parking area. However, during 16.00-17.00, the errors are 0.7 and 1.0 ppm, respectively, due to the decreased wind speed and consequent CO concentration accumulation.

Conclusion

The results of CO concentration predictions correspond mostly to the measurements. At the SNB and KKH intersection, the predicted CO concentrations were close to the observation, except for some hours when the predicted CO concentrations are not in agreement due to the receptor location being upwind, low wind speed or rainy period. While the SCB intersection is located in the central business district area, where it is surrounded by high buildings and near another intersection, the monitoring mobile station was located close to an underground parking lot, therefore the CO concentration observations are higher than the CO concentration prediction for working days. However, this study shows that the CAL3QHC model can be applied to predict CO concentration in Thailand conditions quite well.

Recommendations

According to the limitations of time, budget and other reasons, this study indicates some points that should be of concern when working in the future.

1) The prediction of air pollutant near the roadway intersection is a microscale therefore the emission modeling should be more appropriate for each study area. This study did not determine a specific emission rate for the study area but used the emission rate of the Chiang Mai city.

2) This study adopted only CAL3QHC model for predicting only CO concentrations at only signalized intersections. Thus, other models, other pollutants and other intersection types (e.g., priority intersection, roundabout, etc.) should be considered.

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