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Urban Air Quality Monitoring and Modelling – A Review

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Abstract

Road traffic significantly contributes to ambient carbon monoxide (CO) concentrations in urban environment. The health concerns from CO exposures, CO may be a useful indicator of the transport and dispersion of inert, primary combustion emissions from traffic sources since CO does not react in the near-road environment. The magnitude of the problem and its significance has motivated to have an assessment/review of monitoring and modeling studies in the near-field of urban roadways. This paper discusses comprehensively an overview of air quality monitoring and modeling. The CO modeling studies in the micro environment of urban roadways along with various conditions such as surrounded by high rise buildings, forming street canyons have been reviewed and presented. The CO modeling studies at micro environment of intersection have also been taken into account in review and discussed.

Keywords: Road traffic, urban environment, air quality monitoring, CO modeling

1. INTRODUCTION

Motor vehicles significantly contribute to ambient carbon monoxide (CO) concentrations. All motor vehicles emit CO, but the majority of CO emitted from this source occurs from light-duty, gasoline-powered vehicles. Urban road traffics have been identified as a single major source of air pollution in urban areas (Mukherjee and Viswanathan, 2001) with subsequent adverse human health effects (Chan, *et al.,* 2002; Colvile, *et al.,* 2001). In fact, CO is the result of incomplete fuel combustion that characterize mobile as opposed to stationary pollution sources and therefore, it can be used as an indicator for the contribution of traffic to air pollution (Comrie and Diem, 1999; Heywood,1988). In addition to health concerns from CO exposures, CO may be a useful indicator of the transport and dispersion of inert, primary combustion emissions from traffic sources since CO does not react in the near-road environment (Baldauf et al, 2009). Many studies have been conducted in the past to monitor and predict one of the deadliest pollutants, CO emitted from vehicular exhausts. Considering the magnitude of the problem and its significance, it has become relevant to have an assessment/review of the existing monitoring and modeling studies carried out in this area. This chapter discusses comprehensively the overview of air quality modeling including suitability and applicability of models. The CO modeling studies in the micro environment of urban roadways along with various conditions such as surrounded by high rise buildings, forming street canyons have been reviewed and presented. The CO modeling studies at micro environment of intersection have also been taken into account in reviewing and discussed. Motor vehicle emissions are a significant source of urban air pollution (Colvile et al., 2001; Health Effects Institute, 2009 and 2010). Rapid growth in the number of vehicles and vehicle activity makes this particularly true in cities in developing countries (Riley, 2002; Schipper et al., 2009). The CO concentrations monitoring and modeling studies concerning vehicular pollution near roadways and major intersections in many cities (Bogo, 1999) have reported in the literature.

2. URBAN AIR QUALITY

Suspended particulate matter (PM) is a complex mixture of tiny particles that consists of dry solid fragments, solid cores with liquid coatings, and small droplets of liquid. Fine particles are produced mostly from combustion or burning activities. The level of fine particulate matter in the air is a public health concern because it can bypass the body's natural filtration system more easily than larger particles, and can lodge deep in the lungs. The health effects vary depending on a variety of factors, including the type and size of particles.

Carbon monoxide is a local pollutant in that high concentrations are found only very near the source. The major source of carbon monoxide, a colorless, odorless, poisonous gas, is automobile traffic. Elevated concentrations, therefore, are usually only found near areas of high traffic volumes. Carbon monoxide's health effects are related to its affinity for hemoglobin in the blood. At high concentrations, carbon monoxide reduces the amount of oxygen in the blood, causing heart difficulties in people with chronic diseases, reduced lung capacity and impaired mental abilities. *Ozone* is produced by chemical reactions, involving nitrogen oxides (NOx) and reactive organic gases (ROG) that are triggered by sunlight. Because ozone is not directly emitted to the atmosphere, but is formed as a result of photochemical reactions, it is considered a secondary pollutant. Ozone is a strong irritant that attacks the respiratory system, leading to the damage of lung tissue. Asthma, bronchitis, and other respiratory ailments as well as cardiovascular diseases are aggravated by exposure to ozone.

Nitrogen oxides (NOx) are produced from burning fuels, including gasoline and coal. Nitrogen oxides react with some varieties of hydrocarbons to form smog, which can harm health, damage the environment, and cause poor visibility. Additionally, NOx emissions are a major component of acid rain. Health effects related to NOx include lung irritation and lung damage. *Sulfur dioxides* (SO_2) is commonly produced by fossil fuel combustion. In the atmosphere, SO_2 is usually oxidized by ozone and hydrogen peroxide to form sulfur trioxide (a secondary pollutant). In addition, the exhaust from diesel engines contains hundreds of different gaseous and particulate components, many of which are toxic. Many of these compounds adhere to the particles, and because diesel particles are so small, they penetrate deep into the lungs. Diesel engine particulate has been identified as a human carcinogen. Mobile sources, such as trucks, buses, automobiles, trains, ships and farm equipment, are by far the largest source of diesel emissions.

3. AIR QUALITY MONITORING STUDIES

Akula Venkatram et al. (2007) detected elevated concentrations, compared to over all urban background levels, of motor-vehicle emitted compounds, including carbon monoxide (CO), nitrogen oxides (NOx), coarse (PM_{10}), fine ($PM_{2.5}$), and ultrafine (PM_1) particle mass, particle number, black carbon (BC), polycyclic aromatic hydrocarbons (PAHs), and benzene in their air quality monitoring studies conducted near major roadways and findings have been supported by host of researchers such as Kim et al., 2002; Hutchins et al., 2000; Zhu et al., 2002a, b; Kittelson et al., 2004). The predicted CO concentrations showed reasonable agreement with annual average and 24-hour measurements, e.g., 59% of the 24-hr predictions were within a factor of two of observations in the warmer months when CO emissions are more consistent. Emmanuel et al (2010) reported the diurnal trend in CO generation and distribution at several road junctions and motor parks in Benin City. Diurnal variations in the data were statistically significant ($P < 0.05$), with the highest CO concentrations recorded in the morning hours. Spatial variations were also statistically significant, with the highest mean CO load of 28.3 ppm measured at Sokponba road junction. However, recent research has determined that traffic-related pollution levels next to busy roadways are much higher than at those fixed locations or at background urban locations (Mukerjee, et. al., 2009). Depending on variables such as wind direction, roadside pollution decreases with increasing distance from the roads (Zhu et. al, 2002b). Escamilla-Nunez et al., 2008; Mukerjee et al., 2009; Singer et. al, 2004; Van Roosbroeck et al., 2007 validated the reciprocal accuracy of data from fixed site monitoring stations and the passive sampler.

4. AIR QUALITY MODELS

Models are widely used in science to make predictions and/or to solve problems, and are often used to identify the best solutions for the management of specific environmental problems. An atmospheric dispersion model is a:

- mathematical simulation of the physics and chemistry governing the transport, dispersion and transformation of pollutants in the atmosphere
- means of estimating downwind air pollution concentrations given information about the pollutant emissions and nature of the atmosphere.

Dispersion models can take many forms. The simplest are provided in the form of graphs, tables or formulae on paper. Today dispersion models more commonly take the form of computer programs, with user-friendly interfaces and online help facilities. The process of air pollution modeling contains four stages (data input, dispersion calculations, deriving concentrations, and analysis). The accuracy and uncertainty of each stage must be known and evaluated to ensure a reliable assessment of the significance of any potential adverse effects.

More recently, better ways of describing the spatially varying turbulence and diffusion characteristics within the atmosphere have been developed. The *new generation* dispersion models adopt a more sophisticated approach to describing diffusion and dispersion using the fundamental properties of the atmosphere rather than relying on general mathematical approximation. This enables better treatment of difficult situations such as complex terrain and long-distance transport.

4.1 Major Existing Air Quality Models

Plume-rise models

In most cases, pollutants injected into ambient air possess a higher temperature than the surrounding air. Most industrial pollutants, moreover, are emitted from stacks or chimneys and possessing, thus, an initial vertical momentum. Both factors (thermal buoyancy and vertical momentum) contribute to increasing the average height of the plume above that of the smokestack. Plume-rise models calculate the vertical displacement and general behaviour of the plume in this initial dispersion phase. Both semi-empirical and advanced plume-rise formulations are available.

Gaussian models

The Gaussian plume model is the most common air pollution model. It is based on the assumption that the plume concentration, at each downwind distance, has independent Gaussian distributions both in the horizontal and vertical direction. Almost all the models recommended by the U.S. Environmental Protection Agency are Gaussian. Gaussian models have been modified to incorporate special dispersion cases. A simplified version of Gaussian model, the Gaussian climatological model, can be used to calculate long-term averages (e.g. annual values).

Semi-empirical models

This category consists of several types of models which were developed mainly for practical applications. In spite of considerable conceptual differences within the category, all these models are characterised by drastic simplifications and a high degree of empirical parameterizations. Among the members of this model category are box models and various kinds of parametric models.

Eulerian models

The transport of inert air pollutants may be conveniently simulated by the aid of models which solve numerically the atmospheric diffusion equation, i.e. the equation for conservation of mass of the pollutant (Eulerian approach). Such models are usually embedded in prognostic meteorological models. Advanced Eulerian models include refined submodels for the description of turbulence (e.g. second-order closure models and large-eddy simulation models).

Lagrangian models

As an alternative to Eulerian models, the Lagrangian approach consists in describing fluid elements that follow the instantaneous flow. They include all models in which plumes are broken up into elements such as segments, puffs, or particles. Lagrangian models use a certain number of fictitious particles to simulate the dynamics of a selected physical parameter. Particle motion can be produced by both deterministic velocities and semi-random pseudo-velocities generated using Monte Carlo techniques. Hence, transport caused by both the average wind and the turbulent terms due to wind fluctuations is taken into account.

Chemical modules

Several air pollution models include modules for the calculation of chemical transformation. The complexity of these modules ranges from those including a simple, first-order reaction (e.g. transformation of sulphur dioxide into sulphates) to those describing complex photochemical reactions. Several reaction schemes have been proposed for simulating the dynamics of interacting chemical species. These schemes have been implemented into both Lagrangian and Eulerian photochemical models. In Eulerian photochemical models, a three dimensional grid is superimposed to cover the entire computational domain, and all chemical reactions are simulated in each cell at each time step. In the Lagrangian photochemical models a single cell (or a column of cells or a wall of cells) is advected according to the main wind in a way that allows the injection of the emission encountered along the cell trajectory.

Receptor models

In contrast to dispersion models (which compute the contribution of a source to a receptor in effect as the product of the emission rate multiplied by a dispersion coefficient), receptor models start with observed concentrations at a receptor and seek to apportion the observed concentrations at a sampling point among several source types. This is done based on the known chemical composition of source and receptor materials. Receptor models are based on mass-balance equations and are intrinsically statistical in the sense that they do not include a deterministic relationship between emissions and concentrations. However, mixed dispersion-receptor modeling methodologies have been developed and are very promising.

Stochastic models

Stochastic models are based on statistical or semi-empirical techniques to analyse trends, periodicities, and interrelationships of air quality and atmospheric measurements and to forecast the evolution of pollution episodes. Several techniques are used to achieve this goal, e.g. frequency distribution analysis, time-series analysis, Box-Jenkins and other models, spectral analysis, etc. Stochastic models are intrinsically limited because they do not establish cause-effect relationships. However, statistical models are very useful in situations such as real-time short-term forecasting, where the information available from measured trends in concentration is generally more relevant (for immediate forecasting purposes) than that obtained from deterministic analyses.

4.2 Suitability of Air Quality Models

The extent to which a specific air quality model is suitable for the evaluation of source impact depends upon several factors. These include: (1) The meteorological and topographic complexities of the area; (2) the level of detail and accuracy needed for the analysis; (3) the technical competence of those undertaking such simulation modeling; (4) the resources available; and (5) the detail and accuracy of the data base, i.e., emissions inventory, meteorological data, and air quality data. Appropriate data should be available before any attempt is made to apply a model. A model that requires detailed, precise, input data should not be used when such data are unavailable. However, assuming the data is adequate, the greater the detail with which a model considers the spatial and temporal variations in emissions and meteorological conditions, the greater the ability to evaluate the source impact and to distinguish the effects of various control strategies.

4.3 Applications of Air Quality Models

The typical applications of air quality models include environmental regulatory purpose, monitoring and overall research purpose. To assess the present quality and prediction for future helps a lot to the authority for proper planning, designing and policy matter.

Regulatory Purposes

Model results are used in issuing emission permits (usually for single sources), or for environmental impact studies related to, for example, industrial plants and in new roads. In general terms, models in this application area have to provide spatial distribution of high episodic concentrations and of long-term averaged concentrations for comparison with air quality guidelines. A wide range of pollutants is modeled (e.g. SO_2, NO_2, suspended particles, but also toxic substances like heavy metals and organics).

Policy Support

The effect of abatement measures has to be forecasted by the models. This may require that the model also give reliable results under pollution conditions, which differ strongly from the present situation. Use of atmospheric models in combination with models for other compartments for example soil, water but also emission modules) in order to obtain a more integrated approach is becoming more and more important. For practical reasons this might imply that more simplified models without losing essential information has to be developed.

Public Information

In public information the role of models is expected to grow. Requirements for public information parallel to a large extent those for policy support as far as it concern assessment studies. On-line information to the public will be needed concerning- air quality. Occurrence of smog episodes will have to be forecasted.

Scientific Research

Among the major objectives for research type models are the description of dynamic effects and the simulation of complex chemical processes involving air pollutants. Until very recently, this type of models proved in most cases not to be suitable for practical applications'. Their requirement on computational effort was too high for application in above three fields. The situation is rapidly changing in favor of complex research type models. Hence, models of this type are not only valuable for identifying limitations and gaps in simpler policy oriented models they could represent the proper policy supporting models in the near future.

5. URBAN ROADWAY DISPERSION MODELS

Thermal and mechanical turbulence occurring behind a vehicle contributes to mixing the emissions, so that the air behind a vehicle is relatively well-mixed. In many situations the modeling of roadway emissions is carried out using a Gaussian-plume model configured to emulate the dispersion of contaminants from this type of line source. Estimating the type and quantity of contaminants emitted from roadways is inherently complex because emissions vary according to:

- the driving cycle (e.g. accelerating, steady speed, decelerating, idling)
- roadway conditions (e.g. free flow or congested)
- vehicle fleet composition
- traffic volume.

Because of these complexities, roadway modeling often requires an emissions model to meet the input data requirements of the model.

5.1 CALINE – 4 Model

CALINE-4 has been developed by the California Department of Transportation and the US Federal Highways Agency for assessing roadway traffic emissions. It is based on the Gaussian diffusion equation and employs a mixing zone concept to characterize dispersion over the roadway. CALINE4 is a Gaussian-plume model and as such is subject to the same limitations of other steady-state Gaussian-plume models. CALINE4 can model roadways, intersections, street canyons, parking areas, bridges and underpasses. Each CALINE run allows the prediction of up to eight one-hour mean concentrations. Therefore, it is useful for investigating one-hour concentrations of NO_2 and CO and eight-hour concentrations of CO.

The US EPA lists CALINE4 as the preferred/recommended roadway model (US EPA, 1999). The UK Department of the Environment, Transport and the Regions lists CALINE4 as an advanced model (UK DETR, 2000) but does not indicate any form of approval or endorsement. The revised *CALINE4* user's guide is relatively straightforward and user friendly (Coe, D., et al., 1998). *CALINE4* has an intersection modeling option for carbon monoxide that should not be used. That option uses a modal model based on testing of a handful of mid- to late-1970's vehicles; modern vehicles with computer controlled combustion and 3-way catalysts are not represented by the outdated modal information included in *CALINE4*. For intersections, an average speed approach such as that outlined in the CO Protocol (Garza, et al., 1997) should be used. In addition to evaluating CO and PM dispersion, *CALINE4* incorporates the Discrete Parcel Method for estimating 19 NO2 concentrations. Also, unlike *CAL3QHCR*, *CALINE4* is capable of analyzing the dispersion of pollutants in winds with speeds of less than 1 m/s [Coe, D., et al., 1998]. In addition, Caltrans makes available to users a simplified version of *CALINE4*, known as *CL4*, that includes a user-friendly graphic user interface (Bryan et. al., 2006).

5.2 URBAN ROADWAY DISPERSION MODELING STUDIES

The studies include, driver variability's impacts on vehicular emission rates (Holmen and Nemeier, 1997) and a better estimation of emissions directly related to vehicle operating modes (Bath et. al., 1996) such as idle, steady-state cruise, and various levels of acceleration/deceleration. In terms of vehicular emission dispersion models, one of the most widely used models is the CALINE series model. The CALINE series models assume that vehicular emissions from traffic roadways can be represented by a "line source" and disperse in a Gaussian distribution (Benson, 1979 & Benson, 1989). The California Department of Transportation (Caltrans) published the first CALINE series model in 1972, and it was replaced by CALINE2 in 1975. Because of the over-predictions by CALINE2 under certain situations (e.g. stable, parallel wind directions) (Benson, 1979), CALINE3 was released in 1980. CALINE3 uses the same Gaussian dispersion methodology but different vertical and horizontal dispersion curves modified for the effects of surface roughness, averaging time, and vehicle-induced turbulence (Benson, 1979). Also, the concepts of mixing zone and equivalent finite line source were introduced into CALINE3 (Benson, 1979). The latest released version of CALINE models is CALINE4, which is an updated and expanded version of CALINE3. The real differences between CALINE3 and CLINE4 are in the areas of improved input/output flexibility and expanded capabilities (e.g. special options for street canyon/bluff effects and parking facilities are provided in CALINE4). In addition to CALINE series models, several other models have been developed to estimate (CO) near intersection in the last decade. These models include IMM (Intersection Middle-block Model), GIM (Georgia Intersection Model), EPAINT (EPA Intersection), FHWAINT (FHWA Intersection) and TEXIN2 (Texas Intersection) (Bullen & Carpics, 1986; Peterson, 1980; Griffin, 1980; Sculley, 1989; Zammers, 1980; Zammers & Robbert, 1991; USEPA, 1992). These models and CALINE series models differ in their analysis of emission rate and CO dispersion algorithm along roadway segments (Sculley, 1989). CAL3QHC and CAL3QHCR are computer programs that incorporate the CALINE3 line source dispersion model and a traffic algorithm for estimating the number of vehicles queued at an intersection (Eckhoff et. al., 1995). CAL3QHCR has been recommended by EPA for modeling (CO) at intersections. CAL3QHCR accepts large meteorological data files and also requires substantial user inputs: emission factors, hourly traffic volume, signalization data, intersection geometry, receptor locations, and hourly meteorological data such as wind speed, wind direction, ambient temperature, and atmospheric stability class. Intersection LOS is a measure of traffic volume, signal timing, and related congestion and delay. It is only dependent on the averaged stopped delay (ASD) per vehicle at the intersection (TRB, 1994). However, the study conducted by UC Davis (Meng & Nemeier, 1997 & Meng & Nemeier, 1998) showed that there are other major factors beyond LOS/ASD that have significant impacts on the modeled CO at intersections. These factors include intersection orientation, intersection geometry, and traffic volume. Very few studies have been conducted to develop an appropriate framework for determining critical intersections in terms of CO impacts. Luhar and Patil (1989) presented a general finite line source model (GFLSM) wherein by adopting a suitable coordinate transformation, the model could be used for all wind angle. In these cases, simple models can provide as good results as computations with more sophisticated models (Hanna, 1971; Gifford and Hanna, 1973; Mazzeo and Venegas, 1991; Berkowicz, 2000; Hanna et al., 2002). Other modeling techniques include Lagrangian models (e.g., Thomson, 1987; Tinarelli et al., 1998; Oettl et al., 2001) and empirical models (e.g., Chock, 1977; Dirks et al., 2002, 2003).

Sharma et al. (1999) used the extreme value theory for predicting the number of violations of the national ambient air quality standards (NAAQS) for an urban road intersection where the primary source of pollution was vehicular exhausts. For the same intersection, Sharma and Khare (2000a, 2000b.) used the Box-Jenkins modeling techniques to, respectively, investigate the impact of legislation to control vehicular pollution (intervention analysis), and provide short-term, real-time forecasts of the ambient air pollution levels due to vehicular sources. Many models have been developed and applied to simulate the line source emission dispersion in the rural open highway, such as the General Motors (GM) line source model (Chock, 1978), California line (CALINE) source models (Benson, 1979) and Highway (HIWAY) air pollution models (Zimmerman and Thompson, 1975). Luhar and Patil (1989) presented a general finite line source model (GFLSM) for all wind directions based on the Gaussian diffusion equations. The prediction performance of GFLSM was compared with GM, CALINE-3 and HIWAY-2 models and a reasonable accuracy for the Indian traffic conditions was shown (Sharma and Khare, 2001; Nagendra and Khare, 2002).

An extensive review of roadside dispersion models and their evaluation against experimental datasets has been presented by Nagendra and Khare (2002). Benson (1992) evaluated the CALINE4 model against data from several independent field studies. He utilized the General Motors experiments (Cadle et al., 1977) and data from measurement campaigns conducted in the United States near major freeways and urban intersections. These comparisons involved measurements of the traffic-originated pollutants CO. Broderick et al., 2003 performed an assessment of CALINE4 for two contrasting sites: a free-flowing motorway and a periodically-congested roundabout.

An extensive review of roadside dispersion models and their evaluation against experimental datasets has recently been presented by Nagendra and Khare (2002) (see also Kukkonen et al., 2001). Venegas and Mazzao (2006) reported the estimations of horizontal distributions of carbon monoxide (CO) and nitrogen oxides (NOx) background concentrations in Buenos Aires City. Anjaneyulu et al. (2006) predicted the CO for 15 links in Calicut city by using CALINE4 and IITLS and Linear regression models. The study has revealed that linear regression model performs better than the CALINE4 and IITLS models. The possible association between CO pollutant concentration and traffic parameters like traffic flow, type of vehicle, and traffic stream speed was also evaluated. Wang et. al. (2006) reported the measured and predicted concentrations of carbon monoxide, CO, fine particles, PM2.5 pollutants, and the traffic and ambient atmospheric conditions at three selected local urban road sites. The predictions were made using general finite line source model (GFLSM) and a high level of agreement was found between the measured and calculated CO and PM2.5 data. Other researchers such as Zoumakis et al., 1994;

Lanzani and Tamponi, 1995; Berkowicz et al., 1997; Vardoulakis et al., 2002b; Gokhale et al., 2005 have validated operational dispersion models (WinOSPM) using datasets from regular street canyons with H/W to1.

5.3 STUDIES ON URBAN STREETS SURROUNDED BY HIGH-RISE BUILDINGS

Some of the most severe air pollution caused by automobile emissions may occur along the street surrounded by high-rise buildings. The modeling of air quality at street, by Johnson et al. (1971) was done by assuming that the wind speed at street level can be extrapolated linearly from the wind speed at the roof level. Chan et al. (1995) compared and evaluated some simple and popular APMs for street canyons. Yamartino and Wiegand (1986) developed simple models for the flow and turbulent fields within an urban street canyon. Berkowicz (1998) developed a robust and simple operational model called operational street pollution model (OSPM). For complicated street canyon, two-step procedure is adopted, the details of which have been reported by Okamato et al. (1994). Several air quality models exist for evaluating roadside air quality (Gokhale and Khare, 2004). However, many of the models are too complex to be operated routinely given the simplicity of the available meteorological and traffic data (Dirks et al., 2003). A few models widely used for evaluating the dispersions at roadside, are for example, the GM (Chock, 1978), the GFLSM (Luhar and Patil, 1989), the CALINE-4 (Benson, 1992), the CAR-FMI (Harkonen et al., 1996), and the UCD models and at street canyons, the OSPM (Berkowicz, 2000; Palmgren et al., 1999) model. Vardoulakis et al. (2003) presented a comprehensive review on the models that evaluates the dispersion within the street canyons.

5.4 STUDIES ON URBAN ROADWAYS INTERSECTION

The CO concentration variation at micro environment of urban roadways intersections has been a subject of a number of publications. It has been observed that pollution concentrations are higher near traffic intersections, where queuing occurs, than at the links (Claggett et al., 1981). This is because vehicles spend longer periods of time near junctions, in driving modes that generate more pollutants viz. queuing, decelerating or accelerating, than the steady cruise. In 1985, Transport Research Board (TRB) developed a hybrid methodology (CAL3Q) based upon the signalised intersection analysis and the deterministic queuing theory. Schattanek et al. (1990) revised CAL3Q to adequately model under- and over- saturation roadway traffic scenarios, i.e. CAL3QHC. In 1989, the USEPA commissioned a performance evaluation of several methodologies that combined emission, traffic, and dispersion models to identify the modeling approach that best estimated CO concentrations near congested intersections. The result of the evaluation showed that of the eight models tested, CAL3QHC performed well in predicting CO concentrations in the vicinity of a congested intersection. Claggett et al. (1981) presented a methodology for identification of the air quality levels near intersections based on diffusion model predictions with little supporting measurements of model validation. This study provided an analysis of CO data collected near a signalised urban arterial intersection. Claggett and Miller (1979) reported CO monitoring and line source model evaluation study for an urban freeway and intersection prepared for the Illinois EPA. Tippichai et al (2005) reported Prediction of CO concentrations from road traffic at signalized intersections using CAL3QHC model. 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. Kho et al (2007) predicted and compared the carbon monoxide (CO) concentration levels along Sembulan Road for years 2004 and 2014 using CAL3QHC air dispersion model at two major locations, i.e., at Sembulan Roundabout and Sutera Harbour Intersection, Kota Kinabalu, Sabah, Malaysia. Comparisons between the modeled and observed outputs using quantitative data analysis technique and statistical methods indicated that the CAL3QHC predicted results correlated well with measured data. It was predicted that receptors located near to the major intersection, in the long-term would be potentially exposed to relatively higher CO levels. Increases in the traffic volume, particularly during peak hours and during special events, results in higher emissions and higher pollutant concentrations. Vehicles that queue up at an intersection, spend a greater amount of time in idle driving mode generating more pollutant emissions per unit time, often leading to higher pollutant concentrations (Gokhale and Khare, 2004, 2005).

6. CONCLUSIONS

The air quality monitoring studies showed that the vehicular exhaust is a major source of CO in urban environment. Frequent traffic jams resulting from poorly maintained roads, high traffic density, un-favorable traffic handling, inadequate traffic discipline and very low wind speed are identified as the main factors responsible for the high emissions, accumulation, and low dilution and dispersion of the generated CO.

In terms of vehicular emission rate models, one of the major developments has been a better understanding of the relationship among different quantities of pollutant emissions and the factors related to different vehicle technological and maintenance characteristics. Many recent studies have improved the ability of vehicular emission rate models to characterize emissions from vehicles operating in real world conditions. When streets are surrounded by high-rise buildings forming canyons, the concentration for the downwind side of the canyon is linearly related to height and is proportional to wind speed and street width, and that the bulk concentration can be determined by dividing the source term by the product of street width and wind speed.

The vehicle driving modes (i.e., idling, accelerating, decelerating and cruising) are variable at intersections, which affect the emission pattern and resulting pollutant concentrations. Therefore, the emission rates are not only determined by the vehicular population but also by the traffic flow patterns and driving modes of the vehicles. These are all in constant fluctuation at busy intersections. In addition, the observed concentrations are also affected by the local meteorology (the wind pattern in particular) and the small-scale turbulence created by the vehicles themselves that change depending on the operating mode of the vehicles.

REFERENCES

[1] Akula Venkatrama, Vlad Isakovb, Eben Thomac, Richard Baldauf (2007), Analysis of air quality data near roadways using a dispersion model, Atmospheric Environment, Vol. 41, pp. 9481–9497

[2] Anjaneyulu, M.V.L.R., Harikrishna M., and Chenchuobulu S. (2006), Modeling Ambient Carbon Monoxide Pollutant Due to Road Traffic, Proceedings of World Academy of Science, Engineering and Technology, Vol. 17, pp. 103 – 106.

[3] Baldauf, R., Watkins, N., Heist, D., Bailey, C., Rowley, P. and Shores, R. (2009), Near-road air quality monitoring: Factors affecting network design and interpretation of data, Air Qual Atmos Health, Vol 2, pp. 1–9

[4] Barth, Matthew, Feng An, Joseph Norbeck, and Marc Ross (1996), Modal Emission Modeling: A physical Approach, *Transportation Research Record* Vol. 15, pp. 20 – 81

[5] Benson, P.E. (1979), CALINE3 – A versatile dispersion model for predicting air pollutant levels near highways and arterial streets. FHWA-CA-TL-79-23, California Department of Transportation, Sacramento, CA.

[6] Benson, P.E. (1989), CALINE4 - A Dispersion Model For Predicting Air Pollution Concentrations Near Roadways Division of New Technology and Research

[7] Benson, P.E (1992), A review of the development and application of the

CALINE 3 and 4 models. Atmos. Environ., Vol. 26B (3), pp. 379 – 390

[8] Berkowicz, R. (2000), A simple model for urban background pollution. Environmental Monitoring and Assessment, Vol. 65, pp. 259–267.

[9] Berkowicz, R., Hertel, O., Larsen, S.E., Sorensen, N.N., Nielsen, M. (1997), Modelling Traffic Pollution in Streets, NERI, Roskilde, Denmark.

[10] Berkowicz, R. (1998), Modelling street canyon pollution: model requirements and expectations. International Journal of Environment and Pollution, Vol. 8 (3–6), pp. 609–619

[11] Berkowicz, R. (2000), OSPM—a parameterised street pollution model. Environmental Monitoring and Assessment, Vol. 65, pp. 323–331

[12] Bogo, H., Negri, R.M., San Roman, E., (1999), Continuous measurement of gaseous pollutants in Buenos Aires city, Atmos. Environ., Vol 33, pp. 2587 – 2598

[13] Broderick B.M., Budd U., Misstear B.D., Jennings S.G. and Ceburnis D. (2003), Validation of air pollution dispersion modeling for the road transport sector under Irish conditions, (Project 2000-LS-6.3-M1): Draft Final Report", Environmental Protection Agency, Johnstown Castle, Co. Wexford.

[14] Bryan D. Jungers, Deb Niemeier, Tom Kear (2006), A Survey of Air Quality Dispersion Models for Project Level Conformity Analysis, UC Davis-Caltrans Air Quality Project, http:/AQP.engr.ucdavis.edu

[15] Bullin, J. A. and Korpics, J. J. (1986), User's Guide to the TEXIN3 Model-a Model for Predicting Carbon Monoxide Concentrations Near Intersections. Texas

[16] Cadle, S.H., Chock, D.P., Monson, P.R., Heuss, J.M., 1977. General motors sulfate dispersion experiment: experimental procedures and results, Journal of Air Pollution Control Assessment, Vol. 27, pp. 33–38.

[17] Chan , L.Y., Hung, W.T., Qin, Y., (1995), Assessment of vehicular emission dispersion models applied in street canyons in Guangzhouh, PRC, Environ. Internat., Vol. 21, pp. 39-46.

[18] Chan, L.Y., Lau, W.L., Zou, S.C., Cao, Z.X., 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, Atmos. Environ., Vol. 36, pp. 5831-5840.

[19] Chock, D.P. (1978), A simple line source model for dispersion near roadways, Atmospheric Environment, Vol. 12, pp. 823–829.

[20] Claggett, M., Miller, T.L. (1979), Final Report: Carbon monoxide monitoring and line source model evaluation for an urban freeway and urban intersection, prepared for the Illinois Environmental Protection Agency, Springfield, IL.

[21] Claggett, M, Shrock, J, Noll, K.E (1981) Carbon monoxide near an urban intersection, Atmos. Environ., Vol. 15, pp. 1633-1642.

[22] Coe, D. (1998), User's Guide for CL4: A User-Friendly Interface for the Caline 4 Model for Transportation Project Impact Assessments (Revised), UC Davis and Sonoma Technology Inc. for Caltrans: Sacramento, CA, http://www.dot .ca.gov/hq/env/air/Documents/CL4Guide.pdf.

[23] Colvile, R.N., Hutchinson, E.J., Mindel, J.S., Warren, R.F. (2001), The transport sector as a source of air pollution, Atmos. Environ., Vol. 35, pp. 1537-1565.

[24] Comrie, A.C., Diem, J.E. (1999), Climatology and forecast modeling of ambient carbon monoxide in Phoenix Arizona. Atmos. Environ., Vol. 33, pp. 5023-5036.

[25] Dirks, K.N., Johns, M.D., Hay, J.E., Sturman, A.P. (2002), A simple semi empirical model for predicting missing carbon monoxide concentrations, Atmospheric Environment, Vol. 36, pp. 5953–5959

[26] Dirks, K.N., Johns, M.D., Hay, J.E., Sturman, A.P. (2003), A semi empirical model for predicting the effect of changes in traffic flow patterns on carbon monoxide concentrations, Atmospheric Environment, Vol. 37, pp. 2719–2724

[27] Emmanuel Ehiabhi Ukpebor, Justina Ebehirieme Ukpebor, Felix Eromomene, Justice Ighodaro Odiase, Duke Okoro (2010), Spatial and Diurnal Variations of Carbon Monoxide (CO) Pollution from Motor Vehicles in an Urban Centre, Polish J. of Environ. Stud. Vol. 19, No. 4 (2010), pp. 817-823

[28] Eckhoff, P. and T. Braverman (1995), Addendum to the User's Guide to CAL3QHCVersion 2.0 (CAL3QHCR User's Guide), U.S. E.P.A. Office of Air Quality Planning and Standards: Research Triangle Park, NC.

[29] Escamilla-Nunez, M. C., Barraza-Villarreal, A., Hernandez-Cadena, L., Moreno-Macias, H., Ramirez-Aguilar, M., Sienra-Monge, J.J., Rio-Navarro B. (2008), Traffic-related air pollution and respiratory symptoms among asthmatic children, resident in Mexico City: The EVA cohort study,

Respiratory Research, Vol. 116, pp. 832-838.

[30] Garza, V. (1997), *Transportation Project-Level Carbon Monoxide Protocol*. 1997, UC Davis - Institute of Transportation Studies: Davis, CA.

[31] Georgii, H.-W. (1969), The effects of air pollution on urban climates. Bulletin of the World Health Organization, Vol. 40, pp. 624–635.

[32] Gokhale, S. and Khare, M. (2004), A review of deterministic, stochastic and hybrid vehicular exhaust emission models, International Journal of Transport Management, Vol. 2, pp. 59-74.

[33] Gokhale, S., and Khare, M. (2005), A hybrid model for predicting carbon monoxide from vehicular exhausts in urban environments, Atmospheric Environment, Vol. 39, pp. 4025–4040.

[34] Gokhale, S.B., Rebours, A., Pavageau, M. (2005), The performance evaluation of WinOSPM model for urban street canyons of Nantes in France, Environmental Monitoring and Assessment, Vol. 100, pp. 153–176.

[35] Griffin, R. (1980), *Air Quality Impact of Signaling Decisions, Program MICR0 User's Guide,* CDOH-DTP-R-80-13, FHWA-CO-RD-80-12, Colorado Department of Highway, Denver, CO.

[36] Gifford, F.A., Hanna, S.R. (1973), Modelling urban air pollution, Atmospheric Environment, Vol. 7, pp. 131–136.

[37] Hanna, S.R. (1971), A simple method of calculating dispersion from urban area sources, Journal of the Air Pollution Control Association, Vol. 21, pp. 774–777.

[38] Hanna, S.R., Britter, R., Franzese, P. (2002), Simple screening models for urban dispersion, Eighth Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, pp. 269–273.

[39] Harkonen, J., Valkonen, E., Kukkonen, J., Rantrakans, E., Lahtinen, K., Karpinnen, A. (1996), A model for the dispersion of pollution from road network, Publications of Air Quality, Vol. 23, pp. 34

[40] Health Effects Institute (2009), Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects. Health Effects Institute, Boston, MA. Special Report 17.

[41] Health Effects Institute, (2010), Outdoor Air Pollution and Health in the

Developing Countries of Asia: A Comprehensive Review. Health Effects Institute, Boston, MA. Special Report 18.

[42] Heywood, J.R. (1988), Pollutant Formation and Control, in Internal Combustion Engine Fundamentals. McGraw-Hill Inc., Science/Engineering /Math, pp. 567-597

[43] Holmén, Britt and Debbie Niemeier (1997), A Missing Link in Automobile Emission Factors: Driver Variability, Journal of the Air & Waste Management Association, Vol. 47, pp. 492–498.

[44] Hotchkiss, R.S., Harlow, F.H. (1973), Air pollution transport in street canyons. EPA-R4-73-029.

[45] Hutchins, J., Morawska, L., Wolff, R., Gilbert, D. (2000), Concentrations of submicrometre particles from vehicle emissions near a major road. Atmospheric Environment, Vol. 34, pp. 51–59.

[46] Johnson, W.B., W.F. Dabberdt, F.L. Ludwig and R.J. Allen (1971), Field Study for Initial Evaluation of an Urban Diffusion Model for Carbon Monoxide, Comprehensive Report CRC and USEPA Contract CAPA -3-68 (1-69, 1971.

[47] Kho, F. W. L., Law, P. L., Ibrahim, S. H., and Sentian, J. (2007), Carbon monoxide levels along roadway. Int. J. Environ. Sci. Tech., Vol. 4, pp. 27-34.

[48] Kim, J.J., Smorodinsky, S., Ostro, B., Lipsett, M., Singer, B.C., Hogdson, A.T. (2002), Traffic-related air pollution and respiratory health: the East Bay Children's Respiratory Health Study, Epidemiology, Vol. 13 (4), pp.100.

[49] Kittelson, D.B., Watts, W.F., Johnson, J.P. (2004), Nanoparticle emissions on Minnesota highways, Atmospheric Environment, Vol. 38 (1), pp. 9–19.

[50] Kukkonen, J., H.ark.onen, J., Walden, J., Karppinen, A., Lusa, K. (2001), Evaluation of the CAR-FMI model against measurements near a major road, Atmospheric Environment, Vol. 35, pp. 949–960.

[51] Lanzani, G., Tamponi, M. (1995), A microscale Lagrangian particle model for the dispersion of primary pollutants in a street canyon, Sensitivity analysis and first validation trials, Atmospheric Environment, Vol. 29, pp. 3465–3475.

[52] Luhar, A.K, Patil, R.S, (1989), A general finite line source model for vehicular pollution prediction, Atmos. Environ., Vol. 23, pp. 555 – 562.

[53] Mazzeo, N.A., Venegas, L.E. (1991), Air pollution model for an urban area. Atmospheric Research, Vol. 26, pp. 165–179

[54] Meng, Yu and Debbie Niemeier (1997), *Modeling Carbon Monoxide Concentrations at Level-of-Service D Intersections*. Final Report. UCD-ITS-RR-98-7. Institute of Transportation Studies, Univ. of California at Davis, Davis CA 95616.

[55] Meng, Yu and Debbie Niemeier (1998), Project Level Carbon Monoxide Hot-spot Analysis for Level of Service D Intersections, Presented at Transportation Research Board (TRB) 77th Annual Conference, January 10 to 15, 1998, Washington D.C.

[56] Mukherjee, P., Viswanathan, S. (2001), Carbon monoxide modeling from transportation sources. Chemos., Vol. 45, pp. 1071- 1083

[57] Mukerjee, S., Smith, L. A., Johnson, M. M., Neas, L. M., & Stallings, C. A. (2009), Spatial analysis and land use regression of VOCs and NO2 from school-based urban air monitoring in Detroit/Dearborn, USA, *Science of the Total Environment, Vol. 407*(16), pp. 4642-4651

[58] Nagendra, S.M.S., Khare, M. (2002), Line source modeling. Atmospheric Environment, Vol. 36, pp. 2083–2098

[59] Oettl, D., Almbauer, R.A., Sturm, P.J. (2001), A new method to estimate diffusion in stable, low-wind conditions, Journal of Applied Meteorology, Vol. 40 (2), pp. 259–268

[60] Okamato, S, Lin, F.C, Yamada, H, Shiozawa, K, (1996), Evaluation of a two-dimensional numerical model for air quality simulation in a street canyon. Atmos. Environ. Vol. 30, pp. 3909-3915.

[61] Palmgren, F., Berkowicz, R., Ziv, A., Hertel, O. (1999), Actual Car fleet emissions estimated from urban air quality measurements and street pollution models, Science of the Total Environment, Vol. 235, pp. 101–109

[62] Petersen, W.B. (1980), *User's Guide for HIGHWAY-2, A Highway Air Pollution Model.* EPA-600/8-80-018, PB 80-227556, US Environmental Protection Agency Environmental Science Research Triangle Park, NC.

[63] Riley, K. (2002), Motor vehicles in China: the impact of demographic and economic changes, Population & Environment, Vol. 23, pp. 479-494

[64] Schattanek, G., Kahng, J., Stratou, T. Braverman, T.N. (Eds.), (1990), EPA

User's Guide to CAL3QHC - A modeling methodology for predicting pollutant concentrations near roadway intersections, USEPA.

[65] Schipper, L., Banerjee, I., Ng, W.S. (2009), Carbon dioxide emissions from land transport in India. Transportation Research Record, 2114, pp. 28-37.

[66] Sculley D. Robert (1989), Vehicle Emission Rate Analysis for Carbon Monoxide Hot Spot Modeling, Journal of Air Pollution Control association, Vol. 39, pp. 1334-1343

[67] Singer, B. C., Hodgson, A. T., Hotchi, T., & Kim, J.J. (2004), Passive measurement of nitrogen oxides to assess traffic-related pollutant exposure for the East Bay Children's Respiratory Health Study, *Atmospheric Environment, Vol. 38*(3), pp. 393-403

[68] Sharma, P, Khare, M, Chakrabarti, S.P, (1999), Application of extreme value theory for predicting violations of air quality standards for an urban road intersection, Transp. Res. – D, Vol. 4, pp. 201-216

[69] Sharma, P, Khare, M, (2000a) Real-time prediction of extreme ambient carbon monoxide concentrations due to vehicular exhaust emissions using univariate linear stochastic models. Transp. Res. - D, Vol 5, pp. 59-69

[70] Sharma, P, Khare, M. (2000b), Short-term, real-time prediction of the extreme ambient carbon monoxide concentrations due to vehicular exhaust emissions using transfer function-noise model, Transp. Res. - D

[71] Sharma, P. and Khare, M. (2001), Modelling of vehicular exhausts: A review, *Transportation Research Part D: Transport and Environment, Vol.* 6, pp. 179-198.

[72] Thomson, D.J. (1987), Criteria for the selection of stochastic models of particle trajectories in turbulent flows, Journal of Fluid Mechanics, Vol. 180, pp. 529–556

[73] Tinarelli, G., Anfossi, D., Bider, M., Ferrero, E., Trini Castelli, S. (1998), A new high performance version of the Lagrangian particle dispersion model SPRAY, some case studies. Preprints of the 23rd CCMS-NATO Meeting, Varna, DEMETRA Publication, 28 September–2 October, pp. 343–350.

[74] Tippichai, A., Klungboonkrong, P., Pan-Aram, R. and Wongwises, P. (2005), Prediction of CO concentrations from road traffic at signalized intersections using CAL3QHC model: the Khon Kaen case study, Songklanakarin, J. Sci. Technol., Vol. 27(6), pp. 1285-1298

[75] Transportation Research Board (1994), *Highway Capacity Manual, Third Edition.* Washington, D.C.: National Research Council, 1994.

[76] United Kingdom Department of the Environment, Transport and the Regions (UKDETR), 2000. *Review and Assessment: Selection and use of dispersion models*.

[77] (URL: http://www.environment.detr.gov.uk/airq/laqm/tg300/pdf/index.htm)

[78] U.S. Environmental Protection Agency (1992), *Guideline For Modeling CO From Roadway Intersections*. Research Triangle Park, North Carolina 27711: Office of Air Quality Planning and Standards, Technical Support Division, November, 1992.

[79] U.S. Environmental Protection Agency (1999), *Evaluation of CO Intersection Modeling Techniques Using a New York City Database, EPA-454/R-92-004,* Office of Air Quality Planning and Standards, Research Triangle Park, NC.

[80] Van Roosbroeck, S., Jacobs, J., Janssen, N. A. H., Oldenwening, M., Hoek, G., & Brunekreef, B. (2007), Long-term personal exposure to PM2.5, soot and NOx in children attending schools located near busy roads, a validation study. *Atmospheric Environment, Vol. 41*(16), pp. 3381-3394.

[81] Vardoulakis, S., Gonzalez-Flesca, N., Fisher, B.E.A. (2002b), Assessment of traffic-related air pollution in two street canyons in Paris: implications for exposure studies, Atmospheric Environment, Vol. 36, pp. 1025–1039.

[82] Venegas, L.E. and Mazzeo N.A. (2006), Modelling of urban background pollution in Buenos Aires City (Argentina), Environmental Modelling & Software, Vol. 21, pp. 577–586

[83] Wang, L. J., Parker, D. B., Parnell, C. B., Lacey, R. E., and Shaw, B. W. (2006), Comparison of Calpuff and ISCST3 models for predicting downwind odor and source emission rates, Atmos. Environ., Vol. 40, pp. 4663–4669

[84] Yamartino, R.J., Wiegand, G, (1986), Development and evaluation of simple models for the flow, turbulence and pollutant concentration fields within an urban street canyon, Atmos. Environ., Vol. 27B, pp. 389-400.

[85] Zoumakis, N.M., Kelessis, A.G., Petrakakis, M., Nikolaou, K., Kozyraki, T.I. (1994), A microscale dispersion model for carbon monoxide emitted from motor vehicles, The Science of the Total Environment, Vol. 146–147, pp. 401–407.

[86] Zammmers, John (1990), Intersection Carbon Monoxide Modeling, Journal of Air Waste Management Association, Vol. 40, No. 5, pp. 760-771

[87] Zammmers, John and Robert Conway (1991), Comparison of Intersection Air Quality Model's Ability To Simulate Carbon Monoxide Concentrations in an Urban Area, Transportation Research Record No. 1312: 23-32. Transportation Research Board, National Research Council, Washington, D.C.

[88] Zimmerman, J.P., Thompson, R.S. (1975), User's Guide for HIWAY. A Highway Air Pollution Model, EPA-650/4-74-008

[89] Zhu, Y., Hinds, W.C., Kim, S., Shen, S., Sioutas, C. (2002a), Study of ultrafine particles near a major highway with heavy duty diesel traffic, Atmospheric Environment, Vol. 36, pp. 4323–4335

[90] Zhu, Y., Hinds, W.C., Kim, S., Sioutas, C. (2002b), Concentration and size distribution of ultrafine particles near a major highway, Journal of Air and Waste Management Association, Vol. 52, pp. 1032–1042