Science of the Total Environment 409 (2011) 1145–1153

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

An open-terrain line source model coupled with street-canyon effects to forecast carbon monoxide at traffic roundabout

Suresh Pandian [a], Sharad Gokhale [b,*], Aloke Kumar Ghoshal [c]

[a] Center for the Environment, Indian Institute of Technology Guwahati, India
[b] Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781 039, India
[c] Department of Chemical Engineering, Indian Institute of Technology Guwahati, India

ARTICLE INFO

Article history:
Received 14 April 2010
Received in revised form 27 November 2010
Accepted 1 December 2010
Available online 8 January 2011

Keywords:
Traffic emission
Air quality
Roundabout
Street canyon
Traffic flow
Dispersion model

ABSTRACT

A double-lane four-arm roundabout, where traffic movement is continuous in opposite directions and at different speeds, produces a zone responsible for recirculation of emissions within a road section creating canyon-type effect. In this zone, an effect of thermally induced turbulence together with vehicle wake dominates over wind driven turbulence causing pollutant emission to flow within, resulting into more or less equal amount of pollutants upwind and downwind particularly during low winds. Beyond this region, however, the effect of winds becomes stronger, causing downwind movement of pollutants. Pollutant dispersion caused by such phenomenon cannot be described accurately by open-terrain line source model alone. This is demonstrated by estimating one-minute average carbon monoxide concentration by coupling an open-terrain line source model with a street canyon model which captures the combine effect to describe the dispersion at non-signalized roundabout. The results of the modeling matched well with the measurements compared with the line source model alone and the prediction error reduced by about 50%. The study further demonstrated this with traffic emissions calculated by field and semi-empirical methods.

1. Introduction

The variability in traffic characteristics such as large traffic volumes, intersections of roads, and accelerating and decelerating fleet dynamics at urban street intersections or roundabouts influences pollutant concentrations within such microenvironments (Lin and Ge, 2006). The increased levels of pollutants in such microenvironments are attributed to. Further, a complex wind flow pattern and strong thermal surface conditions distort the pollutant fluxes, affecting the observed air pollutant levels. At roundabouts, particularly those that are non-signalized, vehicles spiral in and out, change lanes and vary speeds in a circular pattern, resulting in complex emission and dispersion patterns. This generates a zone in which emissions are re-circulated within a road width leading to the canyon-type effect between the continuous moving vehicles. In this zone, an effect of thermally induced turbulence dominates over atmospheric turbulence causing pollutant emission to flow within a small region resulting into more or less equal amount of pollutants upwind and downwind particularly during light wind conditions. Beyond this region, however, the effect of winds becomes stronger causing downwind movement of pollutants. Typical characteristic of roundabout of forcing vehicles to make a lateral displacement around central-island prior to exit has a great effect on the speed of approaching vehicles (Polus et al., 2003). Such dynamics of fleet speed of non-homogeneous traffic further affects the amount and flux of emissions greatly and thereby the concentrations of pollutants. Such complex emission patterns and dispersion processes cannot be described adequately by open-terrain line source models alone.

Most of the simple line source dispersion models, particularly the Gaussian based, do not account for several of these factors which are very typical in traffic intersections or roundabouts microenvironment. Moreover, they simulate downwind pollutant levels and as a result tend to over-predict very close to emission sources where there is no specific flow pattern. In general, these models simulate the dispersion of pollutants near a roadway by treating continually moving vehicles as a pollutant emitting line source. A line source dispersion model treats traffic emission as uniformly distributed across the roadway. The CAL3QHC is one of the models which specifically accounts for several possible factors relevant to traffic intersections both moving and idling vehicles (US EPA, 1995). However, non-signalized roundabout limits the usefulness of such models directly. This is because the traffic is in continuous movement and vehicles are not expected to experience idling mode. Further, Broderick et al. (2004) carried out a study at five-arm traffic roundabout in Galway city using CALINE4 in which the five arms of the roundabout were treated as five line sources meeting at a centre point like a roadway. The results showed that the estimated values for CO were far under predicted and did not capture the diurnal variation. In such microenvironment, the combination of box model

* Corresponding author. Tel.: +91 361 258 2419.
E-mail address: sharadbg@iitg.ernet.in (S. Gokhale).

0048-9697/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.scitotenv.2010.12.003

approach, which captures a street canyon effects within a road section and line source dispersion model for away from road or emission source, could describe the dispersion phenomenon relatively better.

This study presents the results of a model, termed as SC-GFLSM, that combines the STREET urban pollution street canyon (SC) model for within a road section to account for thermal and vehicle induced turbulences and the general finite line source model (GFLSM) for outside the road where the influence of atmospheric turbulence is more. The results of this coupled model are compared with the results of GFLSM. The study further demonstrates the impact of different emission calculation methodologies used in air quality modeling such as field and semi-empirical methods.

The GFLSM model is applicable for all orientation of winds to a line source. Several studies presented the results of its application near traffic intersection and roundabout for non-homogeneous traffic condition. This has been, for example, demonstrated in the studies carried out by Luhar and Patil (1989), Gokhale and Khare (2005) and Gokhale and Patil (2010). The model uses empirically derived mechanical turbulence, i.e. vehicle wake factor, as a function of atmospheric stability (Gokhale and Khare, 2007) and therefore does not capture adequately the intermittent fluctuations of winds and thermally induced turbulence produced in short-time. This may be one of the reasons for which it tends to over-predict when winds are low and wind directions parallel or nearly parallel to the line source as observed by Kono and Ito (1990), Benson (1992), Sivacoumar and Thanasekaran (1999) and Kukkonen et al. (2001). The STREET model is applicable for a street canyon because it calculates concentrations by combining a plume equation for direct impact of vehicle emitted pollutants with a box approach to enable computation of the additional impact due to pollutants re-circulated within streets by vortex flow (Johnson et al., 1973; Yamartino and Wiegand, 1986).

The objective of the present study has been to estimate CO concentration at a measurement point using coupled SC-GFLSM and compare the results with those of GFLSM model. We demonstrated this with three different emission calculation methodologies, the first of which calculates the emission from COPERT-IV speed–emission equations, the second one, from observed traffic density used with semi-empirical method and the third one, on the basis of estimated density with semi-empirical method. The proposed SC-GFLSM model in association with field based and semi-empirically estimated emission rates, describes the non-uniformity of pollutant fluxes generated when vehicles approach, enter and leave the roundabout. This study has been carried out at a double-lane four-arm urban traffic roundabout to estimate one-minute average CO concentration for a period of 30 min. The entire traffic dynamics observed at the site for 30 min was analyzed for capturing every 10 s characteristics of the fleet by video clips which were later averaged to 1 min for calculating emission rates and CO concentrations. The characteristics included: vehicle category, the speed of individual vehicles, traffic density based on measured space mean speed and semi-empirical method, approach time of vehicle, circulatory flow of vehicles, and leaving time of vehicles.

2. Methodology

Fig. 1 shows a traffic roundabout with a measurement location for CO and meteorological station and the names of approaches. The study involved data collection on CO concentrations, traffic characteristics and meteorological parameters such as wind velocity, wind direction, ambient temperature, solar radiation and relative humidity. The meteorological data were measured at 12 m height and the CO concentrations and temperature were measured at 1.5 m from the ground with the help of TSI CO monitor (IAQ-CALC 7545) for every minute interval. Fig. 2 shows CO concentration data for a period of 30 min along with the wind speed, direction and traffic count. Fig. 3 shows the variation of temperature with time. For traffic data, videos

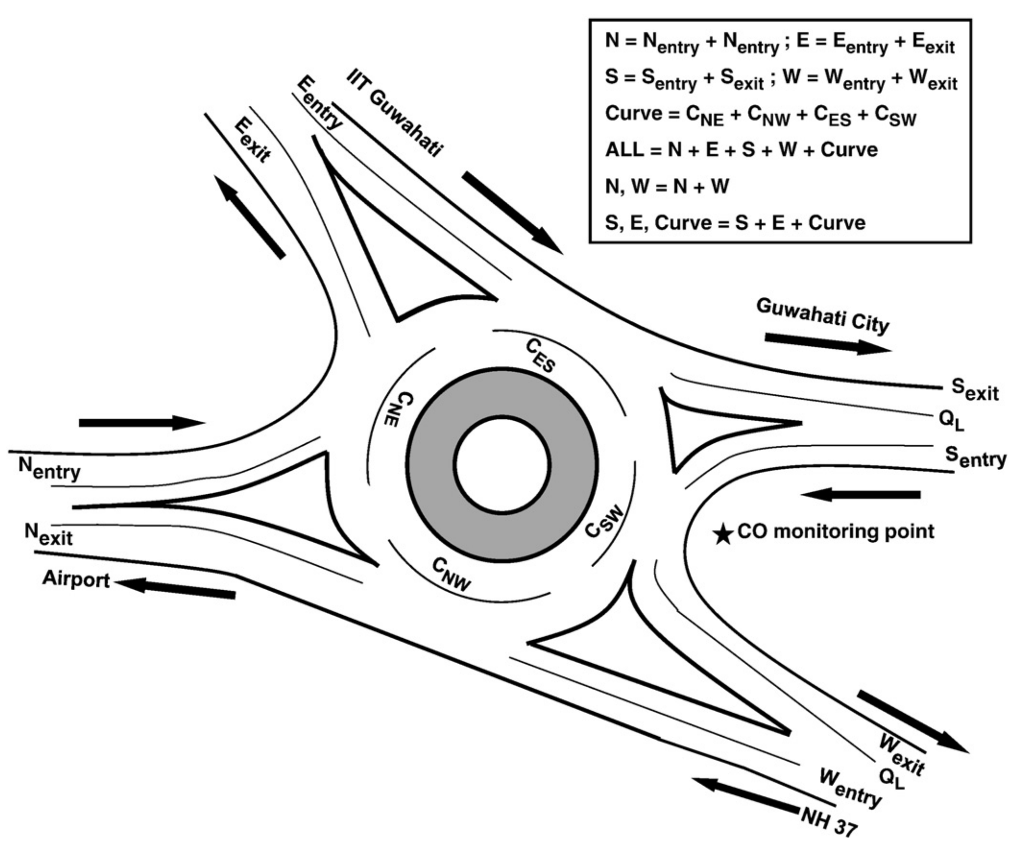

Fig. 1. Double lane four-arm roundabout traffic intersection.