ESTIMATION OF FUEL LOSS AND SPATIAL–TEMPORAL DISPERSION OF VEHICULAR POLLUTANTS AT A SIGNALIZED INTERSECTION IN DELHI CITY, INDIA

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ABSTRACT

Vehicular traffic is considered one of the major contributors to urban air pollution in a city like Delhi. Signalized traffic intersections are considered as urban hotspots due to their high air pollution levels which generally exceed the air quality standards specified by the regulatory agencies. The high air pollution levels mainly result from the idling of a large number of motor vehicles at these signalized intersections resulting in fuel losses and corresponding emissions leading to deteriorating air quality. There are ~950 signalized traffic intersections in Delhi city. A large number of the population works and lives close to these traffic intersections and are exposed to these air pollutants. Therefore, it becomes imperative to understand the spatial–temporal distribution of vehicular emissions resulting because of the idling of motor vehicles at these intersections. In the present study, the fuel loss estimation due to the idling of vehicles was carried out at Lodhi Road intersection using idling fuel consumption data carried out on various test vehicles representing the Delhi traffic. The fuel loss was converted into emissions using fuel-based Intergovernmental Panel on Climate Change (IPCC) emission factors. The emissions have been estimated in terms of greenhouse gas (CO_2, CH_4, and N_2O) emissions and indirect greenhouse gas (CO, NO_x, and NMVOC). The results indicated that daily there was ~230 litre of petrol, ~100 litre of diesel and ~170 kg of compressed natural gas (CNG) loss due to idling at Lodhi Road intersection. The resultant emissions load estimated was ~1300 kg of CO_2, 13 kg of NO_x, 90 kg of CO per day. The spatial extent of vehicular pollutant has been assessed with the help of the CAL3QHC model.

Keywords: emissions, fuel loss, idling, signalized intersection, CAL3QHC model.

1 INTRODUCTION

The traffic intersections are considered as air quality hotspot because of generally poor air quality at these places which often exceeds the stipulated air quality standards. The main reasons for this is high vehicular traffic activities, vehicular idling due to traffic delay, red time signal etc. A vehicle run on a city road trip consists of idling, acceleration, cruise, and deceleration modes [1]. The share of these different stages depends upon driver behaviour, level of traffic congestion at traffic intersections etc. Further, the fuel consumption of vehicles depends upon factors viz. type and category of vehicles, engine technology, inspection and maintenance (I & M) practices etc along with the driving cycle of the city [2], [3]. Large variations in traffic flows, increased queuing time and constricted road geometries makes signalized road intersections as pollution hotspots [4], [5]. The delays at traffic intersections result in idling fuel losses and corresponding emissions which deteriorate the air quality of surrounding areas. A study carried out by Sharma et al. [6] estimated idling fuel losses at 950 signalized traffic intersections in Delhi to be ~262,703 kL petrol, ~145,284 kL diesel, 248 kt CNG and 10,202 kL LPG per year. Further, if these losses converted into monetary terms they estimated to be around 5.9 billion USD per year (1 US$ = 70 Indian Rs.).

The people working, commuting or spending time at these signalized traffic intersections gets exposed to high level of air pollutants. Complexity in dispersion of air pollution at urban intersection makes it difficult to manage air quality at these hotspots. Thus, to manage the air

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quality at these urban hotspots, it becomes more important to understand the extent of spread and dispersion behaviour of pollutant at traffic intersections. The dispersion of air pollutants at traffic intersections get influenced by various factors viz. intersection geometry, surface roughness, wind speed and wind direction etc.. Vehicular pollution dispersion models have been used to predict present and future air quality along the roads/highways. They have been used and have helped in improving the understanding of the pollution dispersion at traffic intersections. There are many line source models (AERMOD, CALINE4, and ADMS) which have been used regularly to predict air quality along road/highway corridors modelling. In the present study, Gaussian equation based CAL3QHC model have been used predict the air quality at a selected traffic intersection. CAL3QHC is an exclusive traffic intersection/ hotspot model. The model has been used in various studies to predict air quality at traffic intersections, however, very few studies have been carried out in India at traffic intersections as well as using this model.

Thus, in the present study, authors have attempted an indicative exercise to estimate emissions due to the idling of vehicles at a signalized intersection in Delhi city. Further, spatial–temporal extent of the vehicular pollution (under mixed traffic conditions) at Lodhi Road intersections has been assessed with help of Gaussian based CAL3QHC intersection model.

2 METHODOLOGY

Delhi city has been experiencing exponential growth in the motorized vehicle population from ~4.3 million in the year 2005 to nearly 10 million vehicles in 2016 [7]. Delhi registered vehicles constitutes nearly 4.22% of the vehicular population of India [8]. Road transport is the main mode of transportation in the city. There are ~950 signalized traffic intersections in Delhi which could be divided into high (>0.2 million vehicles/day), medium (0.1–0.2 million vehicles/day) and low (<0.1 million vehicles/day) traffic intersections according to their traffic volume. The private mode of transportation viz., car, and two-wheelers constitutes ~85% of all traffic volume of Delhi city. Delhi has the highest traffic density, therefore regular traffic congestion and delays at various traffic intersections are not unfamiliar in the city. The selected signalized traffic intersection is located at Lodhi Road (28°35'28.06"N, 77°13'44.24"E) at an elevation of 707 feet (Fig. 1). Lodhi road intersection is a low capacity intersection (<0.1 million vehicles/day) with an average daily traffic volume of ~92,000 vehicles. The Lodhi road intersection is located in a mix of government offices, schools, colleges and residential complexes. However, the surroundings of selected site are relatively greener, spacious and have planned development as compared to most of the Delhi city.

2.1 Estimation of idling fuel losses and corresponding emissions

The methodology for estimation of fuel loss and corresponding emissions at Lodhi Road signalized intersection consists of two parts: (i) carrying out fuel consumption studies at idling on various test vehicles (representatives of vehicles fleet plying on selected city/state). These tests simulate and help in estimating the fuel consumed during idling of vehicles at various signalized intersections; and (ii) converting the fuel losses as estimated in step (i) into emissions by employing appropriate emission factors and various other input parameters collected from primary surveys or secondary sources.

For the estimation of idling fuel consumption, different categories and vintage of (two-wheelers, bike scooters, cars, etc.) petrol-powered and diesel-powered vehicles were tested [6], [9]. The vehicles tested were broadly categorized in the following categories: (i) 2W–4S

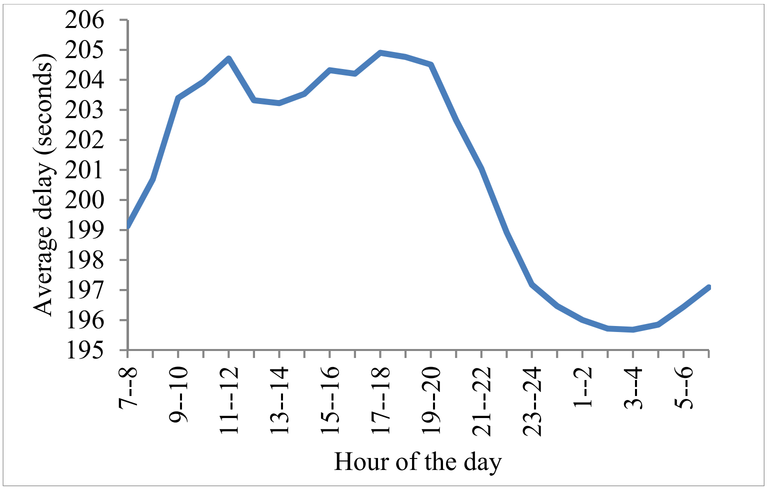

Figure 1: Average delay at Lodhi Road signalized traffic intersection.

(two wheelers–4 stroke-motorcycle); (ii) car–petrol; (iii) car–diesel; (iv) LCV (light commercial vehicles)–diesel; and (v) bus–diesel, HCV (heavy commercial vehicles), 3W (three wheelers)–auto, which form the fleet composition in Delhi.

The total number of vehicles idling at selected intersection due to delay has been estimated by cumulative input–output flow polygon approach [10] are shown in Table 1. From Table 1, maximum idling traffic could be observed during evening hours (17.00–18.00 and 18.00–19.00 hours).

Further, the maximum waiting time could be observed during morning and evening traffic peak hours. During late night hours, traffic delay was observed to be less as compared to day time hours due to low traffic count at intersection (Fig. 1).

Idling fuel consumption was estimated in terms of mass units (kg) then converted in terms of equivalent energy units by applying the fuel specific net calorific values (NCV) for emission estimations (TJ/t). Idling emissions (kg/hour) were estimated using IPCC [11], [12] default pollutant-specific (CO_2, CH_4, CO, N_2O, NO_x and NMVOC) emission factors (kg/TJ) for each fuel type used [13]. The detailed methodology for estimation of idling fuel consumption and corresponding emissions can be referred from [6].

2.2 CAL3QHC model description

CAL3QHC is a Gaussian based mathematical model to predict vehicular pollutants viz., Carbon monoxide (CO) or other inert pollutant from vehicular at traffic intersections. CAL3QHC is a consolidation of the CALINE3 line source dispersion model and an algorithm that estimates the length of the queues formed by idling vehicles at signalized intersections [14]. The model predicts the air pollution concentrations from both moving and idling vehicles. CAL3QHC requires all input parameters necessary to run CALINE4, on addition to these input idling emission rates, number of moving lanes, approach traffic volume at each link, idling emission factors signal cycle length, red time signal, clearance lost time, Saturation flow rate, signal type, and arrival type etc. at the intersection is required. Table 2 presents the input parameters collected/estimated for air quality prediction by CAL3QHC model at Lodhi Road intersection.

Table 1: Hourly idling traffic at Lodhi Road signalized intersection.

Time	Car	2W–4S	Auto rickshaw (3W)	Bus	LCV	HCV
7–8	274	136	94	24	18	0
8–9	394	203	148	21	13	1
9–10	555	338	234	42	17	0
10–11	628	367	255	31	14	0
11–12	654	369	325	25	32	1
12–13	602	299	255	23	22	1
13–14	596	304	246	22	22	2
14–15	612	311	275	14	20	0
15–16	642	373	298	15	23	1
16–17	664	358	269	17	24	0
17–18	758	365	260	23	20	1
18–19	756	366	256	21	12	0
19–20	671	394	262	12	27	0
20–21	564	291	205	18	16	1
21–22	455	238	149	11	14	0
22–23	338	109	73	10	12	4
23–24	171	50	49	5	9	3
24–1	99	29	39	0	6	4
1–2	61	16	21	1	4	3
2–3	30	16	10	0	3	3
3–4	27	10	12	0	5	3
4–5	31	13	28	1	5	5
5–6	84	29	39	9	5	7
6–7	135	53	54	14	6	1
Total	9800	5035	3855	357	348	42
% share	50.4	25.9	19.8	1.8	1.8	0.2

The CAL3QHC model has been used to predict CO concentration under prevailing traffic and meteorological conditions during morning (10–11 am) and evening (6–7 pm) traffic peak hours. The CO being the indicator pollutant for vehicular activities was chosen for the present study.

2.3 Estimation of emission factors

In the present study, hourly emission factors were estimated for twelve links. Out of twelve links, eight were free flow links and four were idling links. Following methodologies were used to estimate the emission factors for both the cases.

2.3.1 Free flow traffic emission factors

The weighted emission factor used in free flow traffic conditions was estimated for the eight links which have free flow conditions. Due to absence of vehicle speed based emission factors, the weighted emission factor (WEF) were estimated on the basis of vehicle kilometre

Table 2: Input parameters for CAL3QHC model.

S. no.	Parameters	Unit/value	Source
(i)	CO measurement (hourly)	mg/m^3 or $\mu g/m^3$	Secondary [15]
Measurement of fuel consumption and free flow/idling emission factors			
(i)	Traffic volume	Vehicles/hour	Primary
(ii)	Categorization of vehicles based on fuel type (petrol, diesel, CNG, LPG) technology type (2 strokes, 4 strokes)	No. of vehicles	Primary and secondary
(iii)	Age profile/vintage of vehicle (fuel station survey)	Number or %	Primary and secondary
(iv)	Fuel consumption by different categories of vehicles during idling (petrol, diesel, CNG and LPG vehicles)	ml/10 min	Primary and secondary [9]
(v)	Average hourly time delay at intersection for each category of vehicle	Seconds (s)	Primary
(vi)	Net calorific value (NCV)	$TJ/10^3$tonne	Secondary [11], [12]
(vii)	Emission factor (EF) (idling)	tonne/TJ	Secondary [11], [12]
(viii)	Emission factor (EF) (free flow traffic)	g/km	Secondary [16]
Meteorological data			
(i)	Wind speed	m/s	Secondary [15]
(ii)	Stability class	Pasquill–Gifford (P–G)	Secondary
(iv)	Mixing height	m	Secondary [17]
(v)	Background concentration	ppm	Primary
(vi)	Multiple wind direction	degree (°)	Primary
(vii)	Wind direction	degree (°)	Secondary [15]
(viii)	Wind direction increment angle	degree (°)	Primary
(ix)	Start angle	degree (°)	Primary
(x)	End angle	degree (°)	Primary
Road geometry			
(i)	Road length	meter (m)	Primary
(ii)	Link height	meter (m)	Primary
(iii)	Mixing zone width	meter (m)	Primary
Queue parameters			
(i)	Average signal cycle length	seconds (s)	Estimated
(ii)	Average red time length	seconds (s)	Estimated
(iii)	Clearance lost time	seconds (s)	Estimated
(iv)	Approach traffic volume	vehicles per hour (vph)	Primary
(v)	Idle emission factor	gram/vehicle-hour (g/v-hr)	Primary
(vi)	Saturation flow rate	vehicle/hour/lane (v/hr/lane)	Estimated
(vii)	Signal type	Pre-timed/ actuated/semi-actuated	Primary
(viii)	Arrival type	Worst/below average/average/ above average/ best progressing	Primary (observed)

travelled based (VKT) emission factors provided by CPCB [16]. The WEF is a function of vehicle emission factor (vehicle category, type, fuel type, age profile, vintage etc.) and vehicle activity (traffic volume). The equation for calculation of WEF is as follows:

$$WEF = [\sum(j)\sum(ky)\ \text{N (j, ky). EF (i, j,ky)]/Total no. of vehicles,} \quad (1)$$

where:

- *WEF* is weighted emission factor (g/km);
- *N (j, ky)* is number of vehicles of a particular type j and age k in year y;
- *EF(i,j,ky)* is emission factor for component i for the vehicle type j and age k in year y (g/km);
- *i* is pollutant component (viz. CO);
- *j* is type of vehicle (i.e. 2W, 3W (auto rickshaw), cars, bus, truck etc.);
- *k* is age of the vehicle in year y.

2.3.2 Idling traffic emission factors

Idling emission factor for CO was estimated and expressed in terms of g/vehicle-hour. The following equation has been used for estimation of–emissions during idling by various categories of vehicles (i)

$$E_i = \frac{[\sum V_{j\,(ky)}.FC_{(j,f,ky)}.D_f.T_{(Jj,f,ky)}.\ NCV_f.EF_{(f,i)}]}{3.6} * 10^6, \quad (2)$$

where:

- E_i = Total emission of pollutants type *i* (kg/h);
- $V_{j\,(ky)}$ = Vehicle type *j* of vintage *ky* (no. of vehicles);
- $FC_{(j,\,f,\,ky)}$ = Fuel consumption during idling by vehicle type *j* using fuel type *f* of vintage *ky* (l/h);
- D_f= Density of fuel *f* (kg/l);
- $T_{(j,\,f,\,ky)}$ (s)= Time delay at traffic intersections by vehicle type *j* of fuel type *f* of vintage *ky*;
- NCV_f=Net calorific value for fuel type *f* (Tera-joule/tonne (TJ/kt));
- $EF_{(f,\,i)}$= Emission factor for fuel type *f* of pollutant type *i* (tonnes/Tera-joule (t/TJ)).

2.4 Meteorological parameters

The micro-meteorological data such as wind speed, wind direction was taken from the IMD air quality monitoring station at Lodhi Road [15]. The hourly mixing height values were obtained from the Indian Meteorological Department (IMD) [17]. The worst case wind angle was considered in the present study with 0 degree as start wind angle and 360 as end angle with 5 degree wind increment angle.

Tables 3 and 4 presents the link-wise input data collected/estimated for the prediction of air quality at the selected traffic intersection. Table 3 presents the input used for free flow traffic link and Table 4 presents the input required for the idling traffic/queue links.

Table 3: Traffic input parameters for free flow traffic links in CAL3QHC model.

Link	No. of vehicles (emission factor, g/mile)		Wind speed (m/s)		Mixing height (m)		Mixing zone width (m)
	10–11 am	6–7 pm	10–11 am	6–7 pm	10–11 am	6–7 pm	
Link 1	1557 (2)	1563 (1.9)	1.1	1.3	1110	1800	14
Link 3	2112 (2)	2130 (1.9)	1.1	1.3	1110	1800	14
Link 4	1729 (2)	1738 (2)	1.1	1.3	1110	1800	14
Link 6	1307 (2)	1549 (2)	1.1	1.3	1110	1800	14
Link 7	1870 (2)	1644 (2)	1.1	1.3	1110	1800	15
Link 8	1388 (2.1)	1817 (2)	1.1	1.3	1110	1800	15
Link 10	1388 (2.1)	1603 (2)	1.1	1.3	1110	1800	15
Link 11	1388 (2)	1603 (1.9)	1.1	1.3	1110	1800	15

Table 4: Traffic input parameters for idling traffic/queue links in CAL3QHC model.

Input parameters	Link 2		Link 5		Link 9		Link12	
	10–11 am	6–7 pm	10–11 am	6–7 pm	10–11 am	6–7 pm	10–11 am	6–7 pm
Average signal cycle length (s)	281	290	281	290	281	290	281	290
Red time cycle (s)	105	107	105	107	105	107	105	107
Clearance lost time (s)	3	3	3	3	3	3	3	3
Approach traffic volume(v/hr)	1201	1581	1386	1381	1186	1308	1373	1360
Idling emission factor (g/hr-v)	2.4	2.3	3.4	3	3.1	4	3.6	4
Saturation flow rate (v/hr/lane)	1800	1800	1800	1800	1800	1800	1800	1800

3 RESULTS AND DISCUSSIONS

3.1 Idling fuel loss and corresponding emissions

The fuel consumption during idling at Lodhi road intersection was estimated for different type and categories of vehicles for 24-hour period. Petrol driven vehicles (especially, private vehicles viz. cars and two-wheelers) are predominantly more in Delhi as compared to public and commercial transport vehicles. Therefore, it was observed that among all fuel type, losses of petrol was highest followed by CNG, diesel and LPG (Table 5).

The diurnal variation of idling emissions viz. NO_x, CO, N_2O, CH_4, NMVOC, and CO_2 has been shown in Fig. 2. Thus, there were idling emission losses to the tune of ~1300 kg of CO_2, 13 kg of NO_x, 90 kg of CO per day. Further, peak idling emissions could be observed during morning and evening peak traffic hours. During night time to early morning hours, when there is less idling traffic at intersection the estimated idling emissions were found to be comparatively very low.

Table 5: Idling fuel loss at Lodhi Road intersection.

Idling fuel loss	**Quantity (per day)**
Petrol	232.14L
Diesel	97.8L
CNG	169.8kg
LPG	10.27L

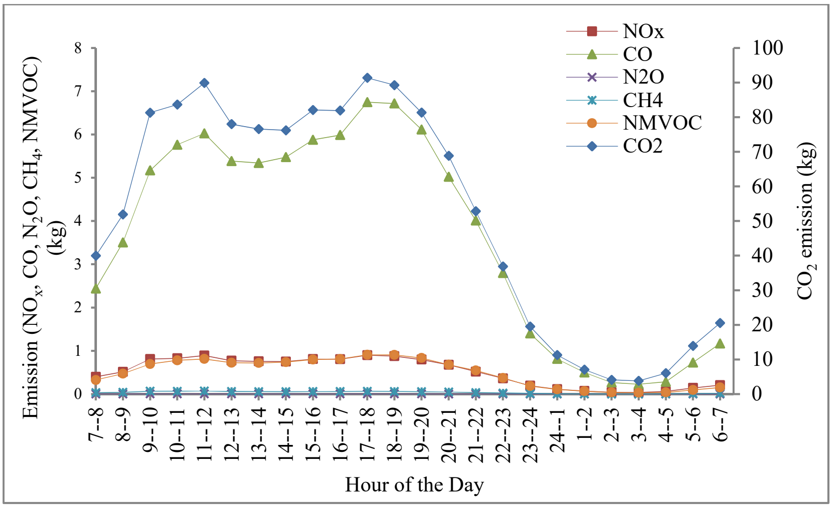

Figure 2: Diurnal variation in idling emissions at Lodhi Road signalized traffic intersection.

3.2 Spatial–temporal extent of emissions at signalized intersection

The spatial extent of vehicular pollutant has been assessed with the help of the CAL3QHC model [14]. Like every typical four arm signalized traffic intersection in India, each arm of Lodhi road intersection has three traffic movements – free left, straight and right turn. Out of these three movements, straight and right movement traffic has to idle at intersection (Fig. 3). In the present study, the spatial temporal extent of pollutants has been observed for morning and evening peak hours only.

The CO concentrations were estimated at pre-identified receptors locations at 2 m, 5 m and 10 m from mixing zone width at its four arms and at centre (middle of intersection). Worst case scenario (in terms of wind angle) selected for the present study and 60 minute average concentration of CO was predicted. The background concentration (input in model) was kept zero to observe only the vehicular emissions contribution to the surroundings. During morning peak hour (10–11 am) the highest concentration was 343.5 μg/m^3 (0.34 mg/m^3) observed at 2 m away from mixing zone width, at distance of 10 m the concentration was zero, indicating absence of contribution from vehicular emission. During the evening peak hour (6–7 pm), the highest CO concentration was observed at centre of intersection (1030.5 μg/m^3 or 1.03 mg/m^3) followed by 2 m (687 μg/m^3), 10 m (572.5 μg/m^3) and 20 m (343.5 μg/m^3) away from mixing zone width, thus indicating reduction in vehicular pollution as the distance from the intersection (or zone of influence) increases (Fig. 4).

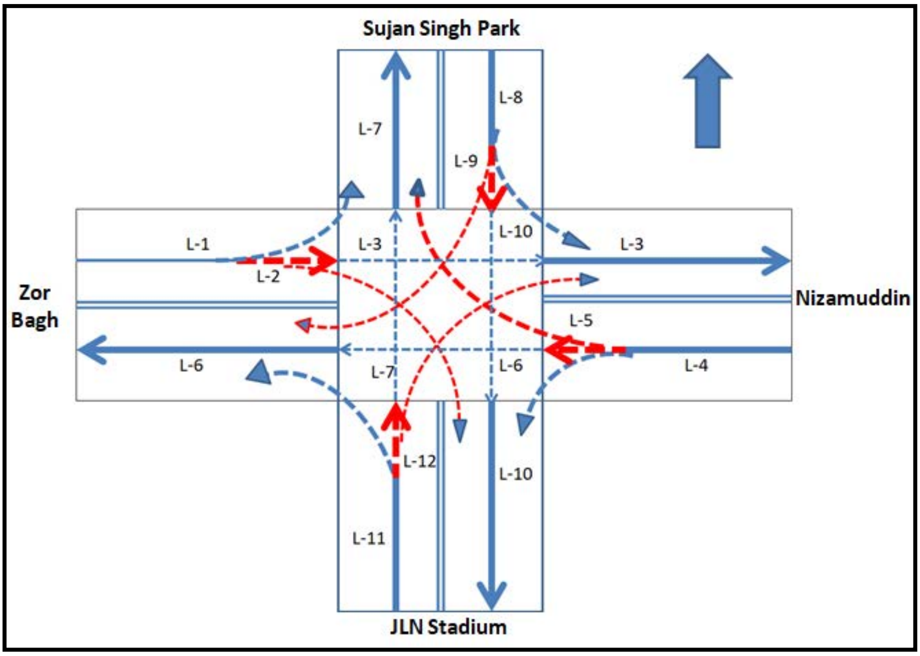

Figure 3: Traffic movement and selected links at Lodhi Road signalized traffic intersection (L = link).

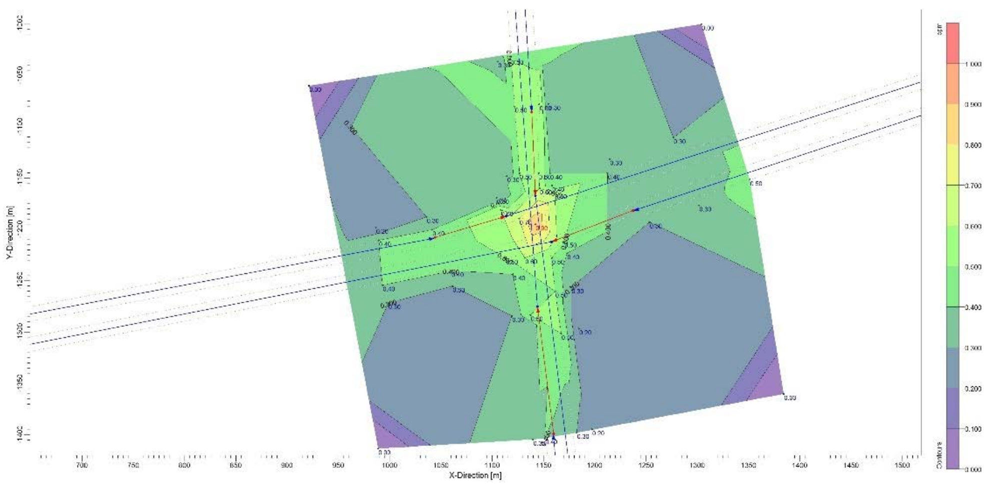

Figure 4: Contour map of CO concentration along Lodhi Road intersection (1800–1900 hours).

During night time (e.g. 2–3 am), due to low traffic volume (~70 vehicles/link/hour), the average signal cycle length (72 seconds) and red time signal (20 seconds) also get reduced which results in smaller queue length and less idling, thus lower CO contribution from vehicles at intersection. Further, ~100 m away from intersection during any time of the day, the vehicular pollutant influence was negligible. When compared to the average observed CO concentration (~1.5 mg/m^3) during evening hour (6–7 pm) from ambient air quality station at Lodhi Road [15], the performance of the CAL3QHC model was found to be satisfactory.

4 CONCLUSIONS

In the present study, idling fuel loss and corresponding emissions were estimated at Lodhi Road intersection in Delhi (India) and an indicative exercise was carried out with the help of CAL3QHC model to understand the spatial and temporal extent of CO dispersion at the selected intersection. The Lodhi road intersection is low traffic capacity intersection with traffic volume of ~92,000 vehicles/day; out of these ~19,000 vehicles idle on an average for ~200 seconds per hour in a day. Large number of petrol driven vehicles (cars, two-wheelers) results in highest loss of petrol fuel followed by CNG (three-wheelers, buses), Diesel (LCV, HCV) and LPG. The fuel loss results corresponding emissions, with highest being CO_2 followed by NO_x, CO, etc. The same exercise could be applied at any signalized intersection to get the estimate of fuel loss and related emission throughout the city in order to find out the enormity of the problem.

Apart from estimation of idling fuel losses and corresponding emissions the spatial and temporal distribution of pollutants holds an important aspect in air quality management studies at these intersections. The spatial and temporal dispersion of pollutants delineate the zone of influence, which could help further in drafting the air quality and traffic management plans. Further, it is necessary to understand the dispersion at intersections because of the exposure level and impact on health of people (due to idling emission and resultants poor air quality) who resides, work or pay short visit at intersections/hotspots due to variety of reasons (viz. commuting, business activity, etc.). The CAL3QHC is Gaussian based intersection model which has been used in the present study to predict the CO concentration. The high concentration observed during the peak hours, (especially during evening peak hours), gives clear indication of the magnitude of contribution of vehicles in deteriorating the air quality in surrounding areas or its influence zone of a traffic intersection. However, the present study is an indicative exercise to present spatial temporal extent of CO in an urban hotspot using CAL3QHC model. The CAL3QHC model has been used in very few studies in India that too under heterogeneous traffic conditions and owing to unavailability or lack of understanding related to traffic and idling/queue link parameters requirement. Studies that are more comprehensive need to be carried out in future for performance evaluation and validation of CAL3QHC model for Indian traffic (heterogeneous or mixed traffic) and meteorological conditions.

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