



Distribution and source apportionment of atmospheric non-methane hydrocarbons in Mumbai, India

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ABSTRACT

Concentrations of non-methane hydrocarbons (NMHCs) in atmosphere were measured at six urban sites in Mumbai from February 2005 to January 2006. Seventeen hydrocarbons, i.e., ethane, ethylene, acetylene, propane, propylene, iso-butane, n-butane, iso-pentane, n-pentane, hexane, benzene, heptane, toluene, ethyl benzene, p-xylene, o-xylene and n-decane have been identified in 254 urban air samples using a cryogenic pre-concentration system attached to a Gas Chromatograph (GC) with a Flame Ionization Detector (FID). C₂–C₅ hydrocarbons were determined on 2 m x 2 mm i.d., stainless steel (S.S.) column packed with n-octane/Poracil C. The components of C₆ and above are determined on a 3 m x 2 mm i.d., S.S. column filled with 10% OV – 101 on chromosorb WAW. All these species show well-defined winter season (November–February) high and summer season (March–June) low values. Factor analysis (FA), a receptor modeling technique, has been used for quantitative source apportionment. Varimax rotated factor analysis identified five possible sources. The mean percent contribution from the vehicular exhausts was found to be 33% while that from refinery sources contribute 21%. Petrochemical industries and paint solvent contributed 15% and 11% respectively. Eight percent of the NMHCs were coming from polymer manufacturing industries. The remaining 12% is contributed by other unidentified sources.

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1. Introduction

Atmospheric non-methane hydrocarbons (NMHCs) play a major role in the complex set of reactions which generate photochemical oxidants such as ozone and peroxyacyl nitrates (PAN) which are extremely injurious to human health and vegetation. Understanding the temporal and spatial characteristics of NMHCs gives insight into likely emission sources and their control strategies. The contributors to the ambient concentrations of NMHCs include natural and anthropogenic sources. Major urban sources of NMHCs are releases from chemical industries, refinery operations, solvent evaporation and vehicular exhaust (Pandit et al., 1990; Liu et al., 2008). The levels of NMHCs in the ambient air are related to the fuels used, vehicle types and ages, flow rates and speeds of traffic as well as road and environmental conditions in the city. The increased aromatics, olefins and other organic compounds in fuels used in vehicles lead to an increase in the emission of volatile aromatic hydrocarbons, especially from vehicles which are not supplied with catalytic converters. Volatile aromatic hydrocarbons represent a significant fraction of gasoline and other fuels as well as automobile exhausts (Liu et al., 2008). In urban atmosphere benzene, toluene and xylenes are the most abundant among the aromatic volatile hydrocarbons (Srivastava et al., 2005). Among benzene, toluene, ethyl benzene and xylenes (BTEX), xylenes are considered the more reactive species with respect to ethyl benzene, whereas benzene has a lower reactivity and more stable in the atmosphere, due to its relatively longer lifetime (Calvert et al., 2002). Xylenes are the most dominant contributor to ozone formation among BTEX (Na et al., 2005). The major sink processes for the NMHCs are their reactions with the hydroxyl and nitrate radicals (Atkinson and Arey, 2003). It is also recognized that halogen atom reactions may also be an important

NMHCs sink in certain areas such as in some coastal regions (Arsene et al., 2007) and in the Antarctic boundary layer (Read et al., 2007).

Some of the hydrocarbons emitted in the atmosphere can have harmful effects on human health and the environment (WHO, 2000). Many NMHCs may lead to ozone production via their reaction with hydroxyl radicals in the presence of sufficient levels of nitrogen oxides. In view of this, information on ambient levels of NMHCs is necessary to evolve a proper strategy for controlling tropospheric ozone buildup and to maintain the desired air quality. Recent improvements in the gas chromatographic techniques have made it possible to analyze many NMHCs which are present in the ambient air. Pre-concentration at cryogenic temperatures with subsequent thermal desorption into a gas chromatograph makes it possible to analyze very accurately the parts per billion (ppb) levels of various NMHCs in the atmosphere.

Multivariate models are important statistical tools used to identify and quantify the sources contributing to the observed aerosol mass. In the multivariate method, one need not make assumptions about the nature and composition of contributing sources unlike chemical mass balance method. Factor analysis, a multivariate method is used in this study for source apportionment. It is a statistical technique which can be applied to a set of variables in order to reduce their dimensionality. That is to replace a large set of inter-correlated variables with a smaller number of independent variables. These new variables (components) are derived from the original ones and are simply linear combinations of those variables.

Considering these, a study has been carried out to determine the ambient levels of NMHCs in the urban atmosphere of Mumbai. Principal Component Analysis (PCA), a receptor model, was applied to the ambient hydrocarbon data to identify probable emission sources for NMHCs in Mumbai city. To quantify the contributions of each source to the measured pollutant multiple regression technique was applied. The results are expected to help better understand chemical emission characteristics in Mumbai urban air. It will also be helpful to formulate pollution control policies and implement air quality standards.

2. Monitoring and Modeling

2.1. Study area

Mumbai (47°N, 73°E) is located at the west coast of India and has a tropical savanna climate with a relative humidity ranging between 57% and 87%. Annual average temperature in Mumbai was 25.3 °C with a maximum of 34.5 °C in June and minimum of 14.3 °C in January. Average annual precipitation is 2 078 mm, with 34% of total rainfall occurring in July. The metropolitan city of Mumbai is one of the rapidly growing cities in India. It has become an epicenter of trade, commerce and industry. A number of industries such as a thermal power plant, a fertilizer plant, two major oil refineries and other chemical industrial units are located in northern suburbs of Mumbai. Increased use of personalized and hired vehicles, buses and goods carriers puts enormous strains on the existing road network. Two wheelers form a major portion of vehicular population. In Mumbai, three wheelers are one of the common modes of transportation.

The major possible emission sources related to the sampling locations were: (i) Diesel internal combustion engines such as trucks, buses, off road equipment, stationery engines for pumps and generators. (ii) Gasoline driven vehicles such as cars, three wheelers, and two wheelers. (iii) Natural gas combustion engines such as buses, four wheelers (taxies) and three wheelers. (iv) Evaporative emissions related to petrol loading and unloading at bulk stations and refueling at retail petrol pumps. Hydrocarbon pollutants also find their way to air through fuel evaporation from vehicles. They can be characterized as running losses, hot soak emissions, diurnal emissions, and resting losses. (v) Surface coating such as emissions from architectural surface coating. In India 70% of paints sold account for decorative segment. (vi) Petrochemical industries, the oil refinery section, where the main activities included regular and reduced pressure distillation, catalytic pyrolysis, catalytic reforming, hydrogen-adding lubricant oil refinery, and gas fractionation, and the major products included gasoline, diesel fuel, kerosene oil, lubricant oil, and naphtha and the chemical industrial section where benzene, styrene and glycol, polyethylene, polypropylene, polystyrene, rubber, ethylene, propylene, and aromatic-related products are produced. (vii) Dry cleaning process uses two general types of cleaning fluids: petroleum solvents like turpentine and synthetic solvents like perchloroethylene and trichlorotrifluoroethane. In metropolitan cities of India, the upper middle class and upper class population generally uses dry cleaning facility. (viii) Newspaper/magazines printing press which uses solvent-borne inks for large scale publication printing. (ix) Liquid petroleum gas (LPG) which is commonly used as fuel in homes and hotels for cooking purposes.

2.2. Sample collection

In the present study, air samples were collected at six different locations as shown in Figure 1. The locations were chosen in different parts of Mumbai so as to represent different characteristics, such as residential, Industrial, traffic junctions, commercial, petrol pumps and remote area. Air samples were collected in Tedlar gas sample bags of 5 liter capacity using a battery operated pump for a period of 2 hours at a height of 1.5 m above the ground level at all chosen locations. Four grab samples

were collected at different times in a day, transported to the laboratory, fully protected from sunlight and analyzed within an hour of collection. The mean values were taken as the representative sample, of that particular day, of that place.

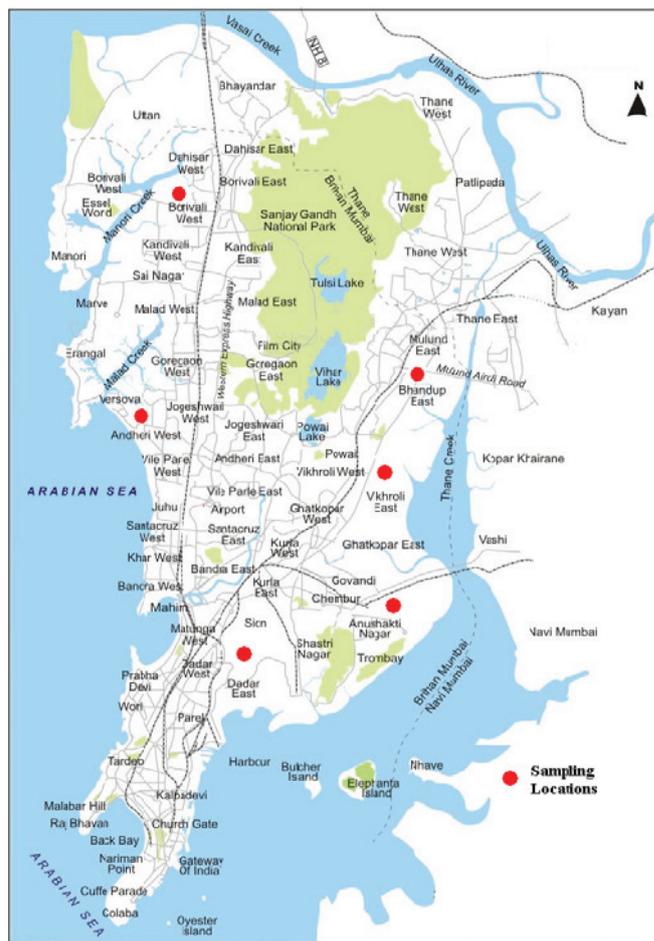


Figure 1. Map of Mumbai showing sampling locations.

2.3. Pre-concentration procedure

The samples were subjected to pre-concentration procedure as given below.

Air sample collected in the Tedlar bag was transferred into an evacuated stainless steel canister of 0.5 L capacity fitted with needle valves at either end. The sample canister was connected to one port of a four port valve V1 and the equalizing canister is connected to another port of the same valve. A U column (30 cm long and 3 mm o.d., 2 mm i.d., partially filled with glass beads of 60/80 mesh) is connected between one port of V1 and another port of V2. The injection port and the inlet of the analytical column of gas chromatograph were connected to two ports of V2. The details about the pre-concentration system and its operation are given elsewhere (Mohan Rao et al., 1997).

2.4. Chemical analysis

The chemical analysis of sample was carried out using Chemito Gas Chromatography. C₂-C₅ hydrocarbons were determined on 2 m x 2 mm i.d., S.S. column packed with n-octane/Poracil C, 80-100 mesh operated at 27 °C isothermal, nitrogen was used as the carrier gas. The flow of nitrogen was 30 mL/min. The components of C₆ and above were determined on a 3 m x 3 mm o.d., S.S column filled with 10% OV - 101 on chromosorb WAW, 80/100 mesh. The operating temperature was 60 °C to 120 °C with programmed heating at 4 °C per minute with zero hold up.

Nitrogen was used as the carrier gas. The flow of nitrogen was 30 mL/min. Flame ionization detector (FID) was used for detection of the hydrocarbons. The gas used for FID was hydrogen with flow rate of 30 mL/min. Using the above operating conditions, n-hexane, heptane, benzene, toluene, p- and o-xylene, ethyl benzene, and n-decane were resolved.

2.5. Calibration of gas chromatograph

For the analysis of blanks, nitrogen was filled into Tedlar bags and entire pre-concentration procedure was followed for estimation of hydrocarbons. The absence of any Hydrocarbons indicated that the entire sampling and analysis line was free from contamination. Calibration was performed by preparing a synthetic mixture in the sampling canister which was analyzed in same way as the samples. There were slight changes in the retention time when the sample was pre-concentrated in the U column and released into GC compared to that obtained from the direct injection of compound into injection port of the GC. Hence, the retention data for all the compounds were generated by trapping the compounds first in the U column and then thermally desorbing into GC. The validity of data was confirmed through different steps. Duplicate run of samples gave results within 10% variation. The calibration runs with standard mixture were conducted weekly. The variation in response of the detector was less than 2% for standard hydrocarbon mixture.

2.6. Receptor models

There has been no investigation providing source composition library of NMHCs for Mumbai city. This limits the usage of the widely accepted chemical mass balance model for source apportionment of NMHCs. Hence, a multivariate analysis technique, i.e., principal component analysis–multiple regression technique, which does not require prior information on source composition was used in this study. The principal component analysis model used in the field of air pollution is expressed as:

$$C_{ij} = \sum_{k=1}^N L_{ik} S_{kj} \quad (1)$$

where C_{ij} is the normalized value of the concentration of the i^{th} species for the j^{th} sample. N is the total number of sources. S_{kj} is the factor score of the k^{th} common factor for j^{th} sample. L_{ik} is the factor loading of the i^{th} species of the k^{th} source (Henry et al., 1984; Hopke, 2000). The detailed description of the FA model can be seen in Okamoto et al. (1990), and Thurston and Spengler (1985). In the present study, we have used the computer software STATGRAPHIC™ for factor analysis which is accurate and easy to use.

The absolute principal component scores (APCS) were used to estimate the source contributions to each pollutant. Since, we performed PCA on standardized (z-transformed) variables; the yielded normalized factor scores cannot be used directly for computation of quantitative source contributions. The normalized factor scores determined subsequently in Equation (1) were converted to non-normalized APCS. Details on the computation of APCS have been described in several publications (Thurston and Spengler, 1985; Okamoto et al., 1990; Johnson and Wichern, 1992). In brief, the preliminary steps involve standardization of all variable concentration as Z_{ij} :

$$Z_{ij} = \frac{X_{ij} - \bar{X}_j}{\sigma_j} \quad (2)$$

where X_{ij} is the measured concentration of variable j in sample i , \bar{X}_j the arithmetic mean concentration of variable j , and σ_j is the

standard deviation of variable j for all samples included in this analysis.

The PCA performed on these standardized variables yield normalized factor scores (A_z) with zero mean and unit standard deviation. An artificial sample with concentration equal to zero for all the variables was introduced to compute absolute zero scores for each factor (Thurston and Spengler, 1985; Okamoto et al., 1990; Johnson and Wichern, 1992), so that:

$$(Z_0)_j = \frac{0 - \bar{X}_j}{\sigma_j} = -\frac{\bar{X}_j}{\sigma_j} \quad (3)$$

The absolute zero factor scores (A_0) for each sample were computed from the values of corresponding factor scores coefficients (S) obtained from PCA performed on standardized variables and the values of (Z_0) computed by above Equation (3) as:

$$(A_0)_k = \sum_{j=1}^J S_{kj} (Z_0)_j \quad (4)$$

J is total number of variables. The absolute principal component scores (APCS) for each sample in each component is then estimated by subtracting the absolute zero factor score values (A_0) of each sample from the corresponding normalized factor scores values (A_z) obtained by PCA of the standardized variables as (Thurston and Spengler, 1985):

$$APCS_k = (A_z)_{ik} - (A_0)_k \quad (5)$$

Finally, the measured concentration data as dependent variables were regressed on mass concentrations of different sources as independent variables, yielding the source contribution to C_j as (Thurston and Spengler, 1985):

$$C_j = (r_0)_j + \sum_{k=1}^F r_{kj} APCS_k \quad (6)$$

where, $(r_0)_j$ is the constant term of multiple regression for pollutant j , r_{kj} is the coefficient of multiple regression of the source k for pollutant j , and $APCS_k$ is the scaled value of the rotated factor k for the considered sample. The combined term, $(r_{kj} \cdot APCS_k)$ represents the contribution of source k to C_j . Moreover, the mean of the product $(r_{kj} \cdot APCS_k)$ on all samples represents the average contribution of the sources (N). Quantitative contributions from each source for individual contaminant were compared with their measured values.

3. Results and Discussion

Table 1 summarizes the ranges and mean concentrations of NMHCs measured at six urban sites in Mumbai during February 2005 to January 2006. The NMHCs composition was similar among all urban sites, indicating a common and dominant source of hydrocarbons. The average profile at all the sites is similar, and key abundant hydrocarbons (i.e., benzene, toluene indicate that motor vehicle emissions are an important source of many of the VOCs at all the sites. The mean concentration of acetylene which is a tracer for auto exhaust is 2.8 ppbv which is much lower than the mean concentrations of other hydrocarbons such as ethylene, propane, pentane, iso-butane, n-butane and benzene. Benzene concentration was found to vary from 3.0 to 25.1 ppbv with a mean concentration of 14.7 ppbv and a standard deviation of 7.0 ppbv at different sampling sites. Toluene has much shorter lifetime than benzene so higher benzene to toluene (B/T) ratio will be found in an aged air via a long range transport. Most of the anthropogenic NMHCs come from vehicle exhaust in urban areas and thus B/T can

be used as a tracer. The B/T ratio of 0.5 was generally used for identification of vehicular exhaust. The present study shows that the mean toluene concentrations are lower than the mean benzene concentrations, and toluene to benzene ratio cannot be utilized to evaluate source contributions in Mumbai. At all the sampling locations B/T values were much higher than 0.5, which indicates apart from vehicular exhaust other sources also contributing to the high observed concentrations for benzene. More complex receptor models are, therefore, required to find out the source contribution.

Table 1. Annual average concentration of NMHCs (ppbv) in the ambient air of Mumbai

NMHC Species	^a LOD (ppbv)	Range	Mean	Std. Dev.
Ethane	0.20	^b BDL-18.5	5.2	4.7
Ethylene	0.20	BDL-16.5	4.3	2.9
Propane	0.30	BDL-17.6	7.8	4.6
Acetylene	0.20	BDL-6.0	2.8	2.2
Propylene	0.20	BDL-40.2	7.1	6.8
iso-butane	0.10	1.3-36.7	10.1	9.6
n-butane	0.10	4.0-62.6	22.2	16.9
iso-pentane	0.20	2.8-86.9	28.2	19.0
n-pentane	0.20	2.5-94.7	26.7	23.1
Hexane	0.10	1.9-22.3	12.8	7.4
Benzene	0.10	3.0-25.1	14.7	7.0
Toluene	0.10	1.4-10.3	4.1	2.5
Ethyl benzene	0.30	BDL-19.0	4.4	2.1
p-Xylene	0.30	BDL-6.1	2.1	1.6
o-Xylene	0.20	BDL-3.5	2.1	1.4
Heptane	0.20	BDL-13.5	4.3	3.0
Decane	0.20	1.2-24.9	13.1	9.4

^a LOD Limit of detection equals three times the standard deviation of the replicate analysis of the lowest standard ($n = 6$)

^b BDL: Below Detection Limit

Figure 2 shows the percentage contribution of individual hydrocarbons to the TNMHCs at six different sampling locations around Mumbai, India. Hexane contribution to the TNMHCs is maximum in the Bhandup sampling location, which is near the industrial belt. At all other sampling locations benzene and toluene contributed maximum to the measured TNMHCs. This indicates vehicular pollution is the major contributor to the TNMHCs in Mumbai. During the sampling period, the concentrations of C_2 – C_{10} varied from 81.8 ppbv to 359.8 ppbv. The variations in the concentrations depended on the downwind or upwind position of the sampling station with respect to the source. The concentrations varied from 21.8 ppbv to 328.7 ppbv for C_2 – C_5 and from 31.1 ppbv to 80.2 ppbv for C_6 – C_{10} , respectively. C_2 – C_5 concentrations were found to be higher than C_6 – C_{10} concentrations except during the period of October–December.

Figure 3 shows the monthly variations of C_2 – C_5 , C_6 – C_{10} and total NMHCs. All these species show well-defined winter season (November–February) high and summer season (March–June) low values. It is attributed to change in OH radical abundance and transport patterns which drive the seasonal variations in NMHCs. The OH radical concentration is highest over the tropical region and highly dependent on the amount of light and the NO_x levels. Hydrocarbons abundance is fairly well mixed over the winter time when NMHCs mixing ratios are much higher than during summer time (Hakola et al., 2006). The results showed a clear peak for total NMHCs during the period January, C_2 – C_5 compounds being the major contributors.

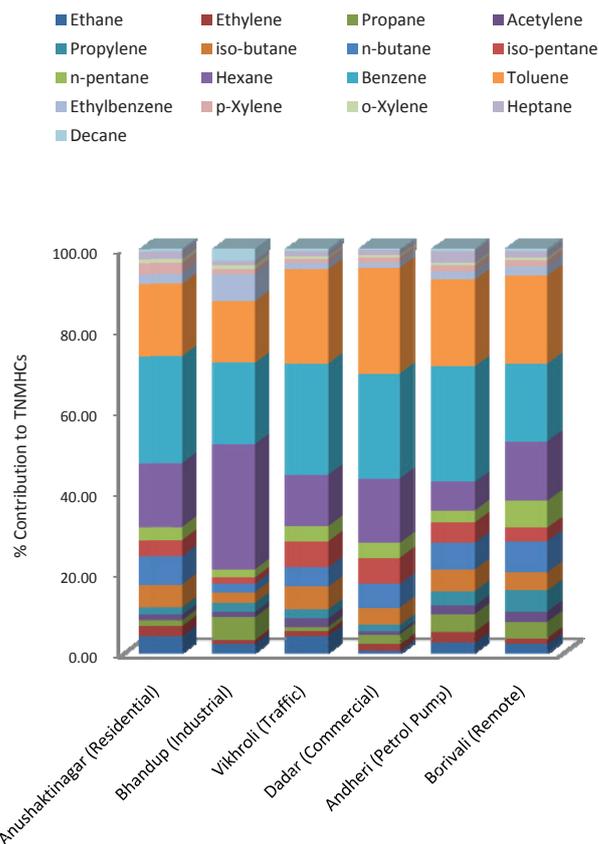


Figure 2. Percentage contribution of individual hydrocarbons to the TNMHCs at different sampling locations.

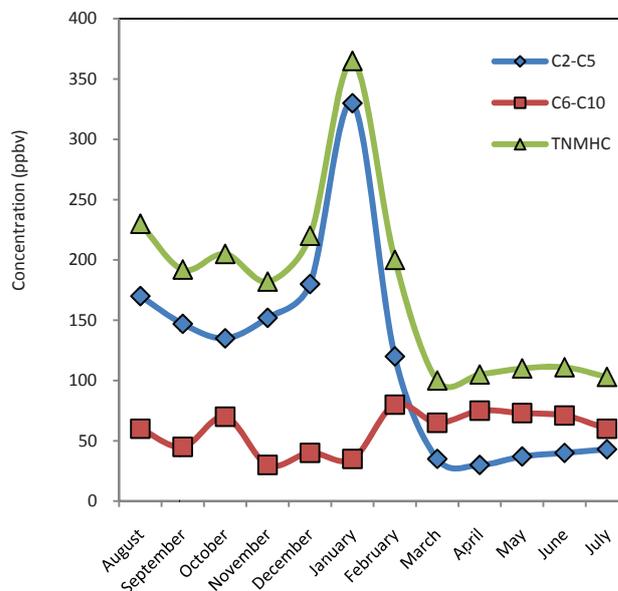


Figure 3. Monthly variation of NMHCs at sampling sites.

Before applying PCA to the NMHC data, individual samples were inspected and those with unusually high or low concentrations were identified as possible outliers. A sensitivity analysis was performed. The suspected outliers were removed from the dataset one at a time until a stable PCA result was obtained and further exclusion of samples in a random fashion had very little

effect on the PCA outputs. The concentration levels of NMHCs which are below detection limits (BDL) pose problems for factor analysis because the programs require complete matrices. The BDL values can be replaced by some constant fraction of the detection limit values (usually one-half) or by some random fraction (by fitting an assumed distribution below the limit). Detection limits are generally distributed randomly and the second replacement method from above cannot be applied. Therefore, in this study, we have replaced below detection limit values with half the detection limit of the respective compounds before applying PCA. Table 2 represents the results of varimax rotated factor analysis carried out on various NMHCs and the corresponding possible sources at Mumbai. Five factors were selected based on the following criteria. Firstly, the number of factors was selected such that the cumulative percentage variance explained by all the chosen factors is more than 80%. Secondly, only the factors with eigenvalues larger than 1.0 were chosen (Singh et al., 2005). Since higher factor loading of marker elements in a factor can help in identifying the possible sources, the number of factors selected should represent the sources, which are relevant in the receptor domain.

Table 2. Factor loading matrix after Varimax rotation

	Vehicular emission	Refinery operation	Petrochemical industries	Paint solvent	Polymer manufacturing industries
Ethane	0.75	0.26	-0.10	-0.19	0.32
Hexane	0.05	0.09	0.06	0.12	0.80
Benzene	0.27	0.14	0.68	0.03	0.17
Heptane	-0.04	0.23	0.78	0.20	-0.01
Toluene	-0.05	0.19	0.41	0.63	0.51
Ethylbenzene	-0.04	0.15	-0.06	0.87	0.02
p-Xylene	0.04	0.27	0.61	-0.04	0.01
o-Xylene	-0.20	-0.04	0.61	0.25	0.47
n-dacane	-0.11	-0.21	0.40	0.64	0.14
Ethylene	0.83	0.06	0.02	-0.05	0.05
Propane	0.48	0.44	0.26	-0.02	0.54
Acetylene	0.72	-0.16	0.03	-0.01	-0.29
Propylene	0.66	0.40	0.15	0.05	0.06
Iso-butane	-0.07	0.79	0.04	-0.10	0.22
n-butane	0.23	0.90	0.10	-0.04	0.06
Iso-pentane	0.13	0.81	0.36	0.24	-0.01
n-pentane	0.15	0.79	0.38	0.17	0.06
% Var	29.57	20.16	15.42	12.18	10.17

The bold written values represent elements having factor loading greater than 0.5 and used for sources identification.

Varimax rotated factor analysis showed five possible groups (based on the factor loading of marker elements greater than 0.5) indicating five different possible sources for NMHCs at the sampling locations. The total percentage of variance explained by five factors was about 87%. The first factor is having high loading for ethane, ethylene, acetylene and propylene which are combustion released species, and hence this factor may be attributed to vehicular emission as a possible source. In Mumbai, fuels used in vehicles are petrol (gasoline), compressed natural gas (CNG) and diesel. Most of the taxis, buses and three wheelers use CNG as fuel. Ethane is mostly emitted from natural gas (Guo et al., 2004). In urban areas, ethylene, propylene and acetylene are mainly emitted from vehicular exhaust (Singh et al., 2005); they are formed during combustion, but are not present in unburned gasoline (Harley et al., 1992). Unburned gasoline emissions, liquid or evaporated gasoline, contain iso-butane, n-butane, n-pentane and iso-pentane (Arsene et al., 2009). Especially, acetylene has been used as a tracer for vehicle exhaust due to its low photochemical reactivity. The second factor was heavily loaded (factor loading > 0.8) with iso-butane, n-butane, iso-pentane and n-pentane indicating refinery operation may be the possible source, particularly the production of liquefied petroleum gas

(LPG) as iso-butane and n-butane are the major constituents of LPG and n-pentane and iso-pentane are the major constituents of petrol. In Mumbai, LPG is commonly used as fuel in homes. Propane is present in natural gas emissions as well as in refinery gas emissions together with n-butane and isobutene (Viswanath, 1994; Na and Kim, 2001). Because of varying rates of oxidation of the vapor-phase organic compounds, some highly reactive species, such as the light olefins, are depleted in a more rapid rate than less-reactive compounds. With transport of emissions from distant sources, atmospheric oxidation removes the reactive species and the remaining fraction contains mostly the less-reactive species, such as ethane and propane. Therefore, having longer lifetimes, ethane and propane tend to accumulate in the atmosphere and may cause an overestimation of natural gas emissions which is determined based on the concentrations of less-reactive alkanes (Watson et al., 2001). The third factor shows high loading for benzene, heptane, o-xylene and p-xylene, indicating the chemical industries as a possible source. Several petrochemical industries around Mumbai city use benzene, heptane and xylenes as raw materials. Benzene is used as raw material to produce alkylbenzene, carpolactam and styrene monomer in the petrochemical industries (Harley and Cass, 1995). The fourth factor has higher factor loading for toluene, ethyl benzene and n-dacane which can be attributed to the paint industries as a possible source. This is because paint samples collected and analyzed showed that toluene, ethyl benzene and n-dacane are the major constituents of the paint (>85%). The fifth factor shows higher factor loading for hexane, toluene and propylene indicating the polymer industries as a possible source which must be using these compounds as input materials for the production of polymer. Multiple regression technique was applied to quantify the contributions of sources to measured NMHCs. Figure 4 gives the percentage contribution from different sources to NMHCs. The mean percent contribution from the vehicular exhausts was found to be 33% while that from refinery sources contribute 21%. Petrochemical industries and paint solvent contributed 15% and 11% respectively. Eight percent of the NMHCs were coming from polymer manufacturing industries. The remaining 12% is contributed by other unidentified sources.

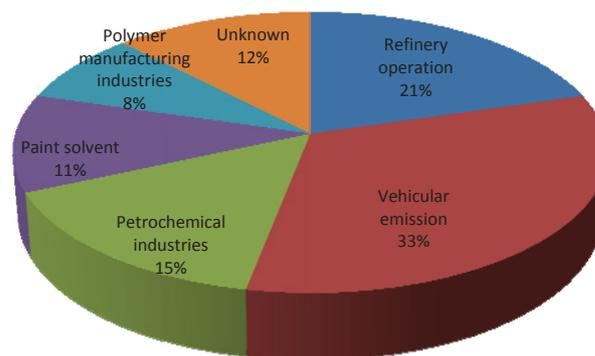


Figure 4. Percentage contribution from different sources to NMHCs.

4. Conclusions

Atmospheric concentrations of seventeen different NMHCs were measured at six urban sites in Mumbai during February 2005 to January 2006. Monthly variations of C₂-C₅, C₆-C₁₀ and total NMHCs shows a clear peak for total NMHCs during the period December-January and C₂-C₅ compounds being the major contributors to the total NMHCs during this period. Generally,

toluene to benzene ratio has been used to evaluate the contribution of vehicular sources to the ambient NMHCs, but the present study shows that the toluene to benzene ratio cannot be utilized to evaluate source contributions in Mumbai. More complex receptor models are, therefore, required to find out the source contribution. Analysis of the data collected at six sites in Mumbai resulted in isolating and evaluating five major source factors. The most important isolated factors affecting these sites were found to be the emissions from vehicular exhaust, refineries, petrochemical production facilities, paint solvent and polymer manufacturing industries. Model-derived source apportionment showed that the combination of vehicle emissions and refineries operation explained 54% of the total VOC emissions, 15% for petrochemical industries and 11% for paint solvent. This study yielded useful and comprehensive information on the distribution and source apportionment of VOCs in a subtropical Asian city.

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