Impact of altitude on emissions of ozone precursors from vehicles

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Abstract
Vehicle emissions are major precursors for the formation of tropospheric ozone that can have adverse effect on human health, building and vegetation. The aim of this study is to investigate the impact of altitude on emissions of ozone precursors (e.g., CO, NOx and VOCs) from light duty commercial vehicles (LDVs) in three Indian cities (Delhi, Dehradun, and Mussoorie). Basic equations of the International Vehicle Emission (IVE) model are applied to estimate emission rates from the LDVs. Topography (altitude) and meteorology (temperature) specific parameters of the IVE model were modified to Indian conditions while estimating emission rates. Unlike NOx, emission rates of CO and VOCs were found to be increasing with increase in altitude, with an opposite trend being with ambient temperature. Findings are important from the health perspective, especially to the public residing in high altitude cities where a peculiar combination of lower oxygen levels and high concentrations of CO and VOCs can adversely affect their health. Also, increased levels of CO and VOCs at high altitudes may considerably influence the chemistry of tropospheric ozone.

Keywords: Air pollution; Vehicle emission rates; IVE model; CO; VOC; Ozone

1. Introduction
Transport sector is one of the major anthropogenic sources of ozone precursors, e.g. NOx, CO and VOCs (Gao, 2007; Matthes et al., 2005; Jiang and Fast, 2004). Vehicular emissions depend on several factors such as type of fuel, driving cycle, engine technologies as well as on topography and climatic conditions (e.g. altitude, humidity, temperature). Altitudes influence the driving pattern and affect the load and pressure conditions inside internal combustion engines that result in altitude-induced changes in vehicular emission characteristics.

Delhi, Dehradun and Mussoorie were selected for this study as these have distinct geographical and meteorological features (see Section 2). While Delhi is a low altitude megacity with a plain topography, both Dehradun and Mussorie are high altitude cities and prominent tourist destinations in Uttrakhand, India. Latter two cities are favorite destinations for visitors from nearby states including Delhi. A large number of tourist travels to these cities that generally peaks during weekends. Since traffic emissions are a large source of ozone precursors, e.g., CO,
NOx, and VOCs (Jiang and Fast, 2004) and the photochemical production of surface (or tropospheric) ozone is also dependent on topographical, meteorological and climatological conditions, it is necessary to examine the impact of altitude on vehicular emissions.

The aims of this study are (i) to estimate the emissions of CO, NOx, VOCs (main ozone precursors) from light duty commercial vehicles (LDCVs) that include passenger cars and taxis, and light trucks) in Delhi, Dehardun and Mussoorie using modified features of the model (IVEM, 2008, Davis et al., 2006) and ii) to investigate the influence of altitude and meteorology on vehicle emitted ozone precursors.

This study presents an approach to assess and evaluate the emission rates in different geographical and climatic conditions by modifying some of the basic equations of the IVE model for Indian conditions. Findings of this study would help air quality control authorities to design future mitigation strategies for vehicle emitted ozone precursors. It may also serve as a tool to estimate vehicular emissions with respect to local topography and meteorology.

2. Methodology

2.1 Study Areas

Monthly variation of temperature in Delhi, Dehardun and Mussoorie are illustrated in Fig. 1. Delhi is located between 28° 24’ 17” N to 28° 53’ 00” North and 76° 50’ 24” to 77° 20’ 37” East in northern part of India with at elevation of 225 m above the mean sea level (MSL). The population of Delhi in 2009 was 19 million (Projected based on Census of India, 2001). As seen in Fig. 1, it has a semi-arid climate with high variation between summer and winter temperatures.

Dehardun (30° 19’ 0” latitude and 78° 2’ 0” longitude) is situated on the south of Shiwalik range of Himalayas at an elevation of 682 m above MSL. Population of Dehardun in 2009 was about 1.5 million (projected based on Census of India, 2001). Besides, Dehardun experience a floating tourist population of about 12 million per year (NIUA, 2007). The average monthly maximum and minimum temperature range between 27 °C and 11 °C. (Fig.1).

Mussoorie (30° 27’ 43” latitude and 78° 04’ 15” longitude) is a highly crowded hill station in Uttarakhand, located on the lower Himalayan ranges with a mean altitude of 1826 m. Population of Mussoorie in 2009 was about 27 thousand (projected based on Census of India 2001). It experiences a floating tourist population of about 3.8 million per year. Mussoorie has a cool climate from April to October (temperature ranging between 6.5 °C and 21.6 °C), with monsoon showering between June and August. Temperature is generally moderate from September to November and snowfall is usually observed in January. The average monthly maximum and minimum temperature ranges between 22 and 6 °C, respectively (Fig. 1).

2.2 Estimation of emission rates from vehicles

Emission rates of CO, NOx, and VOCs from LDCVs (including passenger cars/taxis, small trucks) in all selected cities were estimated using the basic equations of the IVE model (IVEM, 2008). Geography and meteorology specific parameters (e.g. altitude, temperature, and humidity)
were modified for Indian conditions while default values were used for other parameters that are defined in Section 2.2.1 (also see Table 1 for details). Geography and meteorology specific correction factors were extrapolated for actual conditions in Delhi using Eq. (1) and in Dehradun and Mussoorie using Eq. (2). Further, the outcomes of Eqs. (1) and (2) are used as input in Eq. (3) to estimate the adjusted emission rates for various LDCVs. Actual emission rates of CO, NO_x, VOCs are then calculated using Eq. (4) that uses the results of Eq. (3) as input parameters.

2.2.1 Correction factors to adjust various model parameters to Indian conditions: Eq. (3) uses correction factors for seven parameters. Because of the lack of location specific data, an adjustment factor to the base emission rate “K_{(Base)}[t]” has been taken equal to 1 that is default value for IVE model, so is the case with fuel quality correction factor “K_{(Fuel)}[t]” (IVEM BERCF, 2008; IVEM Correction Factor Data, 2008). In addition to this, values for temperature “K_{(Temp)}[t]”, humidity “K_{(Hmd)}[t]”, altitude “K_{(Alt)}[t]”, driving pattern “K_{(dt)}”, and base emission rate “B[t]” have been taken from IVE model dataset, as shown in Table 1 (IVEM Correction Factor Data, 2008).

For estimating emissions from LDCVs in one particular day in each city, actual emission rate was multiplied with average distance travelled in a single day that was assumed as 45.1 km/day (Mashelkar, et al. 2002). To assess the impact of altitude of a particular topography on vehicular emissions, same average travel distance for all three cities are considered. This input was supplied to Eq. (4) for estimating emissions of CO, VOCs and NO_x.

\[ X = \left( \frac{X_{\text{Final}}}{X_{\text{Initial}}} \right)^{\frac{1}{t}} - 1 \times 100 \]  
\[ X_{\text{Final}} = X_{\text{Initial}} \times (1 + x)^{t} \]

where,

- \( X \) : Average geometric growth rate of variable X
- \( X_{\text{Initial}} \) : Value of correction factor at the initial geographical and climate conditions
- \( X_{\text{Final}} \) : Value of correction factor at the final geographical and climate conditions
- \( t \) : Difference between initial and final geographical and climate conditions values

\[ Q[t] = B[t] \times K_{(Base)}[t] \times K_{(Temp)}[t] \times K_{(Hmd)}[t] \times K_{(Fuel)}[t] \times K_{(Alt)}[t] \times K_{(dt)} \]  
\[ E_i = Q[t] \times D \]

where,

- \( E_i \) : Total emission of a pollutant \( i \) (CO, NOx, VOC) (g)
- \( Q[t] \) : Adjusted emission rate for LDCVs (g/km)
- \( D \) : Distance traveled by LDCV in one day (km)
- \( K_{(Base)}[t] \) : Adjustment factor to the base emission rate (assumed as 1)
- \( K_{(Temp)}[t] \) : Temperature correction factor (used as given in Table 1)
- \( K_{(Hmd)}[t] \) : Humidity correction factor (used as given in Table 1)
- \( K_{(Alt)}[t] \) : Altitude Correction Factor (used as given in Table 1)
3. Results and Discussion

3.1 CO emissions

Fig. 2 illustrates monthly variation in emission rates of CO in Delhi, Dehradun and Mussoorie. Whereas, Fig. 1 shows monthly variation in temperature. Both Figs. show similar trend i.e. increased emission rates of CO with increasing temperature. Highest emission rates of CO were observed in June while these were lowest in January that is the coldest month at all three locations (Figs. 1 and 2). One possible reason for higher CO emission rates during summer months could be higher vaporization of fuel due to the use of carburetor air/fuel control technology in most LCDVs resulting in richer air/fuel mixture in vehicle engines.

Fig. 3 shows annual emissions of CO from the LCDVs. It was observed as 273, 291 and 384 kg/year in Delhi, Dehradun and Mussoorie, respectively. This illustrates a gradual increase in total CO emissions with increasing altitude of cities. It should be noted that we have assumed same distance travelled per day (45.1 km/day) by a LDCV in each city. The daily average emission rates of CO also showed similar trend; these were estimated as 17, 18 and 24 g/km in Delhi, Dehradun and Mussoorie, respectively. The IVE model states that CO emissions from carburetor fitted LCDVs should rise with increasing altitude and temperature (IVEM, 2008). Our estimates in regard of altitude agree with the assumptions of IVE model, but disagree in regard of temperature as CO emissions found to be decreasing with increase in altitude. Possible reason for higher CO emissions with increasing altitude could be the gradual decrease in oxygen concentrations that could lead to incomplete combustion of fuel (USDE, 2006) and consequently higher release of CO emissions.

3.2 NOx emissions

Fig. 4 shows monthly variation in emission rates of NOx from the LCDVs in selected cities. The LCDVs emit minimum NOx in June (hottest month of the year); about 0.54 g/km in Delhi and Dehradun and about 0.43 g/km in Mussoorie. After June, monthly emission rates of NOx starts increasing while the temperature declines in all three cities (Fig. 1). In the month of January, emission rates of NOx were highest; these were 0.78, 0.71 and 0.55 g/km in Delhi, Dehradun and Mussoorie, respectively (Fig. 4). This trend from Fig. 1 and 4 clearly indicate that emission rates of NOx decreases with increasing temperature and vice-versa. Fig. 3 shows annual NOx emissions, which were highest for Delhi (~11 kg/yr) and the lowest for Mussoorie (~8 kg/yr). Unlike CO, we find the opposite trend i.e. decrease in NOx emissions with increase in altitude (Fig. 3). It also means that NOx emissions decrease in parallel with temperature with increasing altitude (Fig. 1, 4 and 3). These results are in accordance to the emission rates given by US Environmental Protection Agency for various altitudes, stating an increase in NOx emissions with decreasing altitude (USEPA, 2008). The possible reason for this could be the use of rich fuel/air mixture during combustion at high altitude, resulting in relatively less emission of NOx.

\[ B_{[t]} \]: Base emission rate for LDCVs (g/km) (used as given in Table 1)
\[ K_{[\text{Fuel}][t]} \]: Fuel Quality Correction Factor (assumed as 1)
\[ K_{[\text{dt}]i} \]: Driving Pattern Correction Factors (used as given in Table 1)
3.3 VOCs emissions
Monthly variation in VOCs emission rates in Delhi, Dehradun and Mussoorie are shown in Fig. 5. Similar trends, as those for CO, were observed for all cities (Fig. 5 and 2). Highest emission rate was observed in the hottest month of June that was about 4 g/km. After June, temperature decreases in all three cities, so are the VOCs. The lowest emission rates were found in January (coldest month at all locations); the VOC emission rates were 2.59, 2.71 and 3.14 g/km for Delhi, Dehradun and Mussoorie, respectively. Annual rate of VOC emissions were the highest in Mussoorie (58 kg/yr), followed by Dehradun (51.33/yr) and Delhi (51.13 kg/yr). Similar to CO, altitude again shows a direct proportionality with VOC emissions, but an inverse relationship with temperature (Fig. 3). This was presumably because higher amount of VOCs are emitted due to incomplete combustion or unburned fuel associated with high altitudes and lower temperatures.

4. Conclusions
Emission rates of CO, NOx and VOC from various LDCVs were estimated in three Indian cities and influence of altitude and temperature on them was investigated. Our results indicate the altitude as a dominant factor influencing the emissions of CO, VOC, and NOx from the LDCVs. Unlike NOx, emissions of CO and VOCs increased with increase in altitude. Temperature was second to altitude in influencing emissions. Emissions of CO and VOCs were found to be increasing at high ambient temperature in cities like Delhi and Dehradun while opposite trend was observed for NOx. Thus, this study signifies that consideration of topography (altitude) and meteorology (temperature) specific parameters is necessary to avoid errors in vehicular emission estimations at a given location.

The results presented in this article can have policy implications related to sustainability issues of transportation systems, public health and environmental protection. For example, higher traffic emissions of CO and VOCs, together with favorable atmospheric conditions, in high altitudinal areas can affect the atmospheric chemistry of tropospheric ozone leading to human health problems and vegetation impairment. A combination of lower level of oxygen and higher concentration of CO in high attitudes can adversely affect the public health by enhancing formation of carboxhemoglobin in human blood.

Since this study presents preliminary results and we have analyzed the limited data set, a further study will be useful to strengthen the findings of this work. Furthermore, a detailed study of the influence of vehicle emissions (including all type of road vehicles) in high altitude regions on atmospheric ozone chemistry would be useful to address this issues in a comprehensive manner.

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References


Table 1: Technology description of light duty commercial vehicles and correction factors

<table>
<thead>
<tr>
<th>Description</th>
<th>Auto/Small Truck</th>
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<tbody>
<tr>
<td>Fuel</td>
<td>Petrol</td>
</tr>
<tr>
<td>Weight</td>
<td>Light</td>
</tr>
<tr>
<td>Air/Fuel Control</td>
<td>Carburetor</td>
</tr>
<tr>
<td>Exhaust</td>
<td>None</td>
</tr>
<tr>
<td>Evaporative</td>
<td>PCV</td>
</tr>
<tr>
<td>Age</td>
<td>&lt;79K km</td>
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<td>Index</td>
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**Default Base Emission Rate (g/km) B**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>CO run</td>
<td>22.255</td>
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<tr>
<td>NO(_x) run</td>
<td>2.002</td>
</tr>
<tr>
<td>VOC run</td>
<td>2.7</td>
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**Correction Factor Temperature K\(_{\text{Tmp}}\)**

<table>
<thead>
<tr>
<th>Description</th>
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<tbody>
<tr>
<td>CO Low Temperature Running (4 °C)</td>
<td>1.03</td>
</tr>
<tr>
<td>CO High Temperature Running (40 °C)</td>
<td>1.93</td>
</tr>
<tr>
<td>NO(_x) Low Temperature Running (4 °C)</td>
<td>1.12</td>
</tr>
<tr>
<td>NO(_x) High Temperature Running (40 °C)</td>
<td>0.61</td>
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<tr>
<td>VOC Evap Low Temperature Running (4 °C)</td>
<td>0.80</td>
</tr>
<tr>
<td>VOC Evap High Temperature Running (40 °C)</td>
<td>1.44</td>
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**Correction Factor Altitude K\(_{\text{Alt}}\)**

<table>
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<tr>
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<tbody>
<tr>
<td>CO Medium Altitude Running (950 m)</td>
<td>1.40</td>
</tr>
<tr>
<td>CO High Altitude Running (1700 m)</td>
<td>1.79</td>
</tr>
<tr>
<td>NO(_x) Medium Altitude Running (950 m)</td>
<td>0.83</td>
</tr>
<tr>
<td>NO(_x) High Altitude Running (1700 m)</td>
<td>0.67</td>
</tr>
<tr>
<td>VOC Medium Altitude Running (950 m)</td>
<td>1.18</td>
</tr>
<tr>
<td>VOC High Altitude Running (1700 m)</td>
<td>1.36</td>
</tr>
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**Correction Factor Humidity K\(_{\text{Hmd}}\)**

<table>
<thead>
<tr>
<th>Description</th>
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<tbody>
<tr>
<td>CO Low Humidity Running (20%)</td>
<td>1.00</td>
</tr>
<tr>
<td>CO High Humidity Running (80%)</td>
<td>1.00</td>
</tr>
<tr>
<td>NO(_x) Low Humidity Running (20%)</td>
<td>1.00</td>
</tr>
<tr>
<td>NO(_x) High Humidity Running (80%)</td>
<td>1.00</td>
</tr>
<tr>
<td>VOC/1-3 buta/Form/Acet Low Humidity Running (20%)</td>
<td>1.00</td>
</tr>
<tr>
<td>VOC/1-3 buta/Form/Acet High Humidity Running (80%)</td>
<td>1.00</td>
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**Driving Pattern Correction Factors K\(_{\text{dt}}\)**

<table>
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<th>Value</th>
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<tbody>
<tr>
<td>CO Carbureted non-catalyst gasoline vehicles</td>
<td>0.460</td>
</tr>
<tr>
<td>NO(_x) carbureted non-catalyst gasoline vehicles</td>
<td>0.397</td>
</tr>
<tr>
<td>VOC carbureted non-catalyst gasoline vehicles</td>
<td>1*</td>
</tr>
</tbody>
</table>

Source: Adapted from IVEM Correction Factor Data, 2008;
*Assumed (not given in IVEM Correction Factor Data)
Figure Captions

Figure 1. Monthly average temperature trends in Delhi, Dehradun and Mussoorie over the years 1995-05. Temperature data for Delhi, Dehradun and Mussoorie are taken from Delhi Statistical Abstract (2006), NIC (2009) and Singh (1995), respectively.

Figure 2. Month wise emission rates (g/km) of CO from LDCVs in Delhi, Dehradun, Mussoorie (1995-2005)

Figure 3. Annual emission rates of CO, NOx and VOC per LDCV at different altitudes.

Figure 4. Month wise emission rates (g/km) of NOx from LDCVs in Delhi, Dehradun, Mussoorie (1995-2005)

Figure 5. Month wise emission rates (g/km) of VOC per LDCVs in Delhi, Dehradun, Mussoorie (1995-2005)
Figure 1
Figure 2

![Bar chart showing emissions (g/km) for different months in Delhi, Dehradun, and Mussorie.](image)

- Delhi
- Dehradun
- Mussorie

Month:
- January
- February
- March
- April
- May
- June
- July
- August
- September
- October
- November
- December

Emissions (g/km):
- 0
- 5
- 10
- 15
- 20
- 25
- 30
Figure 3
Figure 4

![Bar chart showing emission (g/km) for different months in Delhi, Dehradun, and Mussorie.](chart_image)
Figure 5