Vehicular pollution dispersion modelling along roads using CALINE4 model – a review

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Abstract: The present paper presents a review of vehicular pollution dispersion models with particular focus on CALINE4 model. The CALINE4 model is one of the most extensively used model for prediction of vehicular pollution along highways/roads. The CALINE4 model is easy handling and less input data requirement makes it useful for screening purposes. The paper also briefly discusses about the performance evaluation, sensitivity analysis of CALINE4 model along with uncertainty due to limitations in terms of input data provided in CALINE4 model’s output.

Keywords: vehicular pollution; dispersion models; CALINE4 model; performance evaluation; mixed traffic.

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1 Introduction

In the past few decades, the vehicular pollution has become a cause of concern. The ambient air quality along roads and highways/areas with high vehicular activity often exceeds the permissible level(s) recommended by respective air quality regulatory standards (Okunola et al., 2012; Balashanmugam et al., 2015). Various studies carried out across the world have clearly established association between health risks and proximity to the major roadway/highway. Various studies have reported that population residing near major roadways are exposed more to high pollutant concentrations than those who live away from roads have increased risks of various diseases (Ingle and Wagh, 2007; Guttikunda and Jawahar, 2012; CSE, 2013). A study carried out on school children reported that children who lived within 500 m of a freeway since age ten had substantial deficit in lung function by the age of 18 years, compared to children living at least 1,500 m away (Gauderman et al., 2007). Thus, due to continuous vehicular activity along the roads and highway, the pollutants concentration is usually higher which require air quality control and management along them. Therefore, vehicular pollution dispersion modelling is regularly used for management of air quality along these roads and highways corridors.

2 Vehicular pollution dispersion modelling

Air pollution dispersion modelling is used to estimate the pollutant concentration in the ambient air using various mathematical models. The main aim of the modelling process is to estimate the concentration of a pollutant at pre-identified receptor points from the basic information related to source of pollutant and meteorological conditions. As large-scale continuous air pollution monitoring is an impractical option for preparation of air quality management plan therefore, vehicular pollution dispersion modelling has emerged as an important tool and has substituted air quality monitoring in control and management of air quality along the roads and highways corridors.

As a result, line source dispersion models have been widely used all over the world for prediction of air quality along road/highway corridors (Malherbe et al., 2010). Various, line source models developed over the years are mostly country or region specific, as they are mostly developed according to their respective traffic, meteorological and terrain conditions. All such traffic and meteorological characteristics are included in the line source models in the form of input parameters. Accuracy, reliability of model’s input parameters influence their predictive capabilities. The meteorological, terrain and traffic characteristics vary from region to region and thus, affects the performance of the models. Further, many times, these models are used without validation and calibration for the regional traffic and meteorological conditions. This issue becomes more vital in developing countries where updated and continuous source of model inputs are not easily available and accurately.

2.1 Types of vehicular dispersion modelling

There are several classifications to describe various air pollution dispersion models (Herczeg, 2013) (Figure 1).
However, these models are broadly classified according to *source type* (point source, line source, area source, volume source, etc.), *source by motion* (mobile or stationary source), *source by duration* (puff/intermittent or long-term or continuous source), etc. Further, air dispersion models could be broadly divided into, physical models and mathematical models (Srivastava and Rao, 2011).

- **Physical models**: simulation of a real process takes place on a smaller scale in order to understand the actual atmospheric behaviour through scale reduction of both the replica and the actual atmospheric flows. The atmospheric wind tunnel is a typical example of physical model in which the atmospheric flows are modelled with real fluids and a small-scale replica of buildings and topographies (Snyder, 1981; Sharma et al., 2004).

- **Mathematical models**: mathematical models represent the physical and chemical process by mathematical equation(s). They are further categorised into *statistical models and deterministic model* (Collett and Oduyemi, 1997). Deterministic and statistical-based approaches are used frequently in line source modelling.
  
  a  **Statistical models**-based on empirical information/data pollution estimates are carried out by statistical analysis of meteorological and other parameters after the statistical relationship has been obtained empirically from measured concentrations, such as, artificial neural networks (ANN), fuzzy logic theory (FLT), etc.
b Deterministic models (analytical and numerical models) are based on a mathematical description of physical and chemical behaviour of pollutants in the atmosphere (Kandya and Mohan, 2009). These models are based on mathematical equations, conservation laws of mass, momentum and energy variables (Goyal and Kumar, 2011).

Models based on the analytical model approach such as Gaussian model, provide solution(s) in the form of basic equations describing the process. In fact, the Gaussian equation-based models are the most widely used models for air quality predictions. They assume that the air pollution dispersion has a Gaussian distribution (i.e., a normal probability distribution) meaning that the pollutant distribution has.

2.2 History of Gaussian-based dispersion models

The history of Gaussian vehicular pollution dispersion modelling ways back to 1930’s when Sutton (1932) presented an expression for the case where the wind is perpendicular to the infinite line source (Stockie, 2011). In 1970’s, a number of studies were carried out to establish relationship between fuel type (petrol and diesel) with atmospheric pollution (Fussel, 1970). Most of such studies were focused on understanding the relationship between various factors/variables (viz., wind speed, stability class, vehicular exhaust, terrain type, etc.), development of new models and their verification. Noll et al. (1974, 1975) reported the relationship between the highways and ambient air quality (Sharma and Khare, 2001). Studies carried out by various researchers (Smith, 1972; Beaton et al., 1972; Calder, 1973; Johnson et al., 1973) focused on understanding the effect of vehicle wake and buoyancy on automobile exhaust dispersion. At the same time various air pollution models, such as CALINE (Beaton et al., 1972), HIWAY (Zimmerman and Thompson, 1975) and GM model (Chock, 1978) were also developed.

Later, further improvements in the Gaussian models were incorporated by studies indicating the correlation between cross-road wind speed and initial vertical dispersion (Chock, 1977; Benson and Squires, 1979; Rao and Keenan, 1980).

Gaussian model’s performance evaluation and verification studies were done with the help of experimental/field studies carried out by Noll et al. (1978), the GM Corporation (Cadle et al., 1976) and the New York State Department of Environment Conservation (NYS) (Rao et al., 1978).

Performance evaluation studies by researchers (Chock, 1977; Noll et al., 1978; Benson and Squires, 1979; Sistla et al., 1979; Rao et al., 1978, 1980; Eskridge and Hunt, 1979, 1983; Green et al., 1979) highlighted the shortcomings of these models, i.e., over-estimation under parallel and under-estimate under oblique/crosswind conditions, non-incorporation of mechanical turbulence in vehicular exhaust dispersion. Further, various studies were carried out to understand the significance of interaction between moving traffic and surface layer structure in the form of aerodynamic drag. Eskridge and Hunt (1979) and Benson (1979) reported that Gaussian models fail to account for change in velocity variance field and turbulence fluctuations. They further concluded that locally generated turbulence is governing factor while atmospheric stability has little role in the near-field dispersion of pollutants.
Most the studies during that time were more focused towards reducing model’s limitations and bring more realistic estimates of vehicular dispersion by incorporating wind speed corrections, modifying dispersion parameters, plume rise due to heated exhaust, treatment of the line source and the consideration of oblique winds, etc. (Sharma et al., 2004). These studies indicated that near field (near roadway) conditions were more dominant in vehicular pollution dispersion than regional scale factors viz., meteorological factors, etc. Simultaneously, Cohn and Gaddipati (1984) and Segal (1983) developed interactive graphics models, which made the modelling exercise more users friendly.

Inferences and interventions of these studies led to the development of new models and up-gradation of the existing line source model over the years. These models included GM (Chock, 1977), HIWAY-2, 3, 4 (Petersen, 1980), CALINE version 2, 3, 4 (Benson, 1989, 1992), Design Manual for Roads and Bridges (DMRB) (DMRB, 1994) and contaminants in the air from a Road-Finnish Meteorological Institute (CAR-FMI) (Harkonen et al., 1996; Harkonen, 2002), ADMS (Carruthers et al., 1994), AERMOD (Cimorelli et al., 2005), California Puff Model (CALPUFF), etc. (Levitin et al., 2005).

Comprehensive reviews by Sharma and Khare (2001), Nagendra and Khare (2002), Sharma et al. (2004) discussed in details about the development of vehicular pollution dispersion modelling. Performance evaluation studies by various researchers (Sharma et al., 2004 and references therein) highlighted the shortcomings of these models, i.e., over-estimation under parallel and under-estimation under oblique/crosswind conditions, non-incorporation of mechanical turbulence in vehicular exhaust dispersion.

Unlike the developed countries, most of the developing countries around the world have heterogeneous traffic conditions. Arasan and Krishnamurthy (2008) suggested that heterogeneous traffic mixes to exist when the percentage of the dominant mode is less than 80% of the traffic mix. Arkatkar (2011) has defined heterogeneous traffic condition where motorised and non-motorised vehicles share the same road space without any physical segregation. In such traffic conditions, speeds of these vehicles vary from just five to over 100 km/h.

Highly varying physical dimensions and speeds makes it difficult to make the vehicles to follow traffic lanes. Heterogeneity in traffic affects the speed of the vehicles and inconsistent acceleration and deceleration results in more tail pipe emissions as compared to lane following and homogeneous traffic. Keeping the heterogeneous traffic conditions in mind, few vehicular dispersion models were also developed. However, these models were city specific and they were computer codes which made their day-to-day usage a bit difficult on project basis as compared to other Gaussian-based.

In developing country like India, keeping the heterogeneous traffic conditions in mind, few vehicular dispersion models, like IITCO (Singh et al., 1990), IIT Line source (IITLS) (Goyal and Krishna, 1999), GFSLM (Luhar and Patil, 1989) and DFLSM (Khare and Sharma, 1999) were also developed. However, these models were city specific and they were computer codes, which made their day-to-day usage a bit difficult on project basis as compared to other Gaussian-based models like, CALINE4, ADMS and AERMOD. Among the Gaussian-based vehicular pollution dispersion models, the CALINE4 model is one of the most extensively used model to prediction of pollutants along roads/highways (Sharma et al., 2013). It is one of the most well developed software packages for analysis of busy road pollution (Gramotnev et al., 2003) which has a wide international acceptance (Burger et al., 2009; Méline et al., 2011).
3 Brief description of CALINE4 model

The development history of the CALINE series of models has been discussed by Benson (1989) and later by Sharma et al. (2004). The CALINE4 is the most recent version of CALINE series model. Benson (1989) incorporated features like prediction of CO, NO\textsubscript{2} and aerosols, modelling at intersection in the CALINE4 model. The model employs modified Gaussian (dispersion parameters, i.e., $\sigma_y$ and $\sigma_z$) similar to CALINE3 model, but provisions for lateral plume spread and vehicle-induced thermal turbulence was incorporated in the model. Sub-models for CO model emissions and reactive plume chemistry were also included. Improved input/output flexibility, estimates of vertical and horizontal dispersions were enhanced by accounting for vehicle induced thermal turbulence and wind direction variability. As in CALINE3 model both emission factor and traffic volume were directly proportional to concentration of pollutant concentration. Further, in CALINE4 model, the vehicle-induced heat flux component of vertical dispersion algorithm alters the direct association between traffic volume and concentration (Benson, 1989).

The CALINE4 model assumes:

1. continuous emission source
2. surface stability classes by Pasquill and Turner
3. concentration of pollutant on highway within mechanical mixing cell is independent of surface stability class
4. uniform wind flow
5. no aerodynamic effect on air passing over the structure.

However, in certain conditions, the model was unable to perform or gave less reliable results viz.: non-steady wind flow/disturbed air flow, street canyon, elevated inversion conditions near enough to surface to influence the surface concentration, low wind speeds, estimation of photochemical pollutant, and adjacent to interchange or intersection (Levitin et al., 2005; Broderick et al., 2006; Dhyani and Sharma, 2017).

CALINE4 model often considered as a reference model against which various other atmospheric models are tested (Ganguly et al., 2009). According to Méline et al. (2011), CALINE4 is considered suitable for modelling air pollution in fairly flat terrain (Pitts, 2004). The CALINE4 vehicular pollution dispersion model is extensively used for prediction of air quality along the highway corridors (Sharma et al., 2013; Dhyani et al., 2013). As indicated earlier, the CALINE4 model requires relatively lesser expertise and has comparatively less input data requirement than other vehicular dispersion models (Gimson and Chilton, 2010). CALINE4 model require relatively lesser expertise and has comparatively less input data requirement than other vehicular dispersion models (Gimson and Chilton, 2010). Most of the models developed are unable to represent solution to real world complexities (e.g., mixed traffic conditions, complex terrain, etc.) present in most of the developing countries and its fair presentation in form of model for different meteorological and traffic condition is still unresolved (Karim et al., 1998).
3.1 Performance evaluation and comparative assessment of CALINE4 model

Although the CALINE4 model has been developed for homogenous traffic conditions and has features to account for vehicle induced turbulence, the model do not take care adequately mixed/heterogeneous traffic conditions, but the model has been used for heterogeneous traffic conditions in developing countries where such traffic conditions exist. Several studies have been carried out around the world regarding performance evaluation of CALINE4 model mostly under flat terrain and homogenous traffic conditions. Ellis et al. (2001) compared the performance of CALINE4 with ADMS-roads and concluded that both models show a tendency to over-predict low concentrations and under-predict high concentrations. Sripraparkorn et al. (2003) applied the CALINE4 model for prediction of PM$_{10}$ and CO concentration in two busy roadside locations in Bangkok (Thailand). The study highlighted the various major and minor factors influencing the model performance and further indicating usefulness of the model at downwind estimation.

Nagendra et al. (2004) carried out the comparison of CALINE4 and GFSLM at two signalised intersections in Bangalore and reported satisfactory performance of the two models. AustRoad (2004) carried out performance evaluation and comparative assessment of HIWAY-2, CALINE4 and GM line source models. The study reported that HIWAY-2 and CALINE4 model performed reasonably well because of their greater versatility. The study further recommended the use of CALINE4 model with more refined/realistic emission rates. Ferdous and Ashraf (2005) applied the CALINE4 model in the Dhaka city (Bangladesh) with heterogeneous traffic conditions exist and found it to be suitable for the application in the city. However, the study concluded careful usage of model as Gaussian model neglects the turning of the wind due to frictional effects and if the plume is reactive, in nature.

Chen et al. (2005) conducted a comparative assessment of three models viz., CALINE4, CAL3QHC and AERMOD for PM$_{2.5}$ in an intersection in Sacramento (California) and (CALINE4 and CAL3QHC only) in a busy road in London (UK). The results indicated that (in Sacramento), the CALINE4 and CAL3HQC model performed well as compared to AERMOD which under-predicted the pollutant concentration. However, in London, CALINE4 and CAL3HQC displayed little coherence with observed values. Levitin et al. (2005) compared the CAR-FMI and CALINE4 model and observed that performance of both models deteriorated as wind speed decreased and wind direction approach parallel to road. This was due to CALINE4 sensitivity to homogenous wind flow and steady state.

Broderick et al. (2006) validated the CALINE4 model for CO in Ireland. They reported that although CALINE4 model performed satisfactorily, most of the times, but its performance deteriorated during low wind and under stable atmospheric conditions. Further, they stress upon the importance of on-site traffic, meteorological and background concentration data for better accuracy of modelling exercise.

Anjaneyulu et al. (2008) predicted and compared the CO pollutant concentration in the city of Calicut (Kerala, India) with CALINE4 and IITLS models with linear regression models. The study reported under-performance by CALINE4 and IITLS model in comparison to linear regression model(s). Further, Ganguly et al. (2006)
R. Dhyani and N. Sharma compared the performance of GFLSM to that of CALINE4 model. The study was aimed to predict speciated hydrocarbon, NO\textsubscript{x} and CO. The study observed that the performance of GFLSM and CALINE4 was. Statistical evaluation carried out as a part of the study also revealed that both models are quite successful in predicting long-term average concentrations.

Delaney (2006) used the CALINE4 model to assess the improvement in air quality after the operation of the newly operated bypass road. The study suggested the accurate dispersion modelling using CALINE4, could be used to predict changes in urban air quality due to major road development activities. Kenty et al. (2007) applied the CALINE4 model to predict the NO\textsubscript{2} in Florida (USA). The model described the measured NO\textsubscript{3} concentration quite well, however, for ambient O\textsubscript{3} concentration less than 40 ppb, CALINE4 model under-predicts NO\textsubscript{2} concentration, suggesting that the simple kinetic used in the model is insufficient to understand the conversion. Further, Yura et al. (2007) reported that the CALINE4 does not perform well in densely populated areas and differences in topography could be a decisive factor when the model was used to predict PM\textsubscript{2.5} concentrations.

Karakitsios et al. (2007) used the CALINE4 model for assessment of health risk associated with contribution of petrol stations to ambient benzene concentrations. Ganguly and Broderick (2008) and Ganguly et al. (2009) compared the performance of GFLSM and CALINE4 model in a selected roadway in Dublin (Ireland) and concluded that GFLSM performance was similar to that of CALINE4. Further, GFLSM marginally outperformed the CALINE4 model and both models revealed good long-term accuracy with monitored data. Gurung (2008) showed the application of Gaussian dispersion model in conjunction with spatial data analysis to illustrate dispersion in the Kathmandu valley and found its performance satisfactory. The study also integrated GIS for identification and visualisation of ‘hot-spot’ of traffic originated air pollutants.

Majumdar et al. (2008) used the CALINE4 model as a base model to develop the correction factor and validated the modified model for the city of Kolkata. Further, the study recommended the use of CALINE4 model with correction factor for regulatory purposes for the city of Kolkata. Goyal et al. (2010) assessed the impact of diesel vehicles on NO\textsubscript{x} and PM emission at various locations in Delhi with two line source models viz., CALINE4 and IITLS. The models under-predicted the observed value, with IITLS predictions being slightly better than CALINE4 predictions due to inclusion of the treatment of low wind (< 1 m/s) conditions in IILTS which is neglected in CALINE4 model. Gokhale (2011) used the three models (CALINE4, CAL3QHC and HV-GFSLM) to assess their performance in urban signalised intersections in Delhi and non-signalised roundabout in Guwahati (India). The study concluded that both CALINE4 and CAL3QHC models performed satisfactorily due to their dynamic responses to traffic changes but CALINE4 responses were slightly better as compare to CAL3HQC. Further, Sharma et al. (2011) used the CALINE4 model to predict the future air quality (CO) after the introduction of metro rail along the road corridor(s) studied. The study concluded that ±10–15% change in weighted emitted factor have minor affect on the CALINE4 predictions. Akyurtlu and Akyurtlu (2012) collected spatial data on NO\textsubscript{x} concentration close to the roadway and compared with model predicted values. They observed that CALINE4 provided inadequate predictions as the actual atmospheric reaction kinetics are not accounted in the model.
Dubey et al. (2013) applied the model in Dhanbad city (India) for CO predictions and compared it with AERMOD. They reported comparatively better performance of the CALINE4 model. Heist et al. (2013) compared the four models viz., RLINE, AERMOD, ADMS and CALINE4 and reported satisfactory performance of all four models for downwind directions. However, the study reported the CALINE4 model’s poor performance at upwind directions and low wind conditions due to differences in explaining the dispersion rates (P-G stability class in CALINE4 and Monin-Obukhov in other three models). Sharma et al. (2013) and Dhyani et al. (2014) carried out the performance evaluation of CALINE4 model for predicting the CO concentration on an urban highway corridor in Delhi. The results have indicated that the dispersion CO concentrations limited to a distance of ~150 m from roads. However, the statistical analysis indicated the CALINE4 model under-predicted the CO values. Dhyani et al. (2017) carried out a study in Delhi (India) on spatial and temporal distribution of PM$_{2.5}$ in the winter and summer season using CALINE4 model along a selected highway in Delhi. The results indicated unsatisfactory performance of CALINE4 model for prediction of PM$_{2.5}$ as there were many uncertainties involved in the predicted results. Factors viz., molecular mass settling velocity, relative humidity which although are instrumental in particulate matter concentration prediction and its spatial distribution were not considered or have little influence on models prediction capabilities.

As indicated above, over the year various comparative studies and performance evaluation studies have been carried out with other vehicular pollution dispersion models, indicating its shortcoming and applicability in various conditions. Due to its wider applicability and acceptance for various road corridors, air quality management plan (EMP) is based on predictions made by vehicular pollution dispersion models such as CALINE4. Future air quality of a region/area along the road corridors depends upon the performance of the air dispersion models used (in that area) for regulatory purpose. Therefore, performance evaluation of models in different traffic, terrain and meteorological conditions and its comparative exercises with other models is important in highlighting its shortcomings and also for development and further improvement of the models.

### 3.2 Sensitivity analysis of CALINE4 model

Uncertainty in the real world could be assessed by carrying out sensitivity analysis of the model (Singh et al., 2007). Sensitivity analysis indicates how much of the overall uncertainty in the model predictions is associated with the individual uncertainty in each model input(s) (McRae and Seinfeld, 1983; Hakami, 2003). Sensitivity analyses explore and quantify the impacts of possible errors in input data on predicted model outputs and system performance indices (Daniel et al., 2005). In various studies, several researchers have indicated the importance of sensitivity analysis exercise in the identification of uncertainties, parameterisation and prioritising the data collection (Nossent et al., 2011; Zhan and Zhang, 2013).

Sensitivity analysis of CALINE4 model was carried out by Benson (1989) comprising most of the input parameters of CALINE4 model viz., stability class, mixing height, wind speed, wind direction, highway width and highway length. However, the
sensitivity analysis exercise was carried out under homogeneous traffic and open terrain conditions. However, few studies have been reported related to sensitivity analysis of CALINE4 model. Moreover, of these, none has been reported for mix traffic and meteorological conditions. Sripraparkorn et al. (2003) used CALINE4 model to predict the roadway contribution of CO and PM$_{10}$ in two roads in Bangkok (Thailand) along with sensitivity analysis of CALINE4 model. The study revealed that wind direction, traffic volume, receptor heights and composite emission factors, affects the output of the model most and atmospheric stability and mixing height affects the output least.

In another study, Dhyani and Sharma (2017) carried out the sensitivity analysis of CALINE4 model under mix traffic conditions. The study concluded that amongst all input parameters studies, wind speed, wind direction, and source strength (emission factors and traffic volume) are most influential input parameters in model.

As discussed above, identification of significant input parameters through sensitivity analysis helps in the development and improvement of existing models. Sahlodina et al. (2007) developed a mathematical model for near-roadway vehicular emission estimation based on the sensitivity analysis conducted on CALINE4 (Benson, 1989; Held et al., 2003), they did not included the surface roughness and stability class in the new developed model due to their insignificant contribution to model’s output. Similarly, Batterman et al. (2010) developed the multiplicative emission and dispersion sub-models by identifying the influential variables through sensitivity analysis of MOBILE6.2 (USEPA, 2004) and CALINE4 model respectively. The sub-model, a reduced model form of CALINE4, did not include the mixing height and stability class due to minor contribution in CALINE4 output.

Such kind of exercises is important to determine the feasibility of the model and its use in different traffic and meteorological conditions. Further, sensitivity analysis exercise makes model more user friendly by focussing on only those input parameters, which are important for prediction of pollutant concentration.

Few exhaustive studies on sensitivity analysis of CALINE4 model have been carried out in western countries, however, most of these studies were set in the conditions which are suitable or congenial (homogeneous traffic and meteorological conditions) for which models has been developed.

Performance evaluation of the CALINE4 model indicated satisfactory performance of the model under both urban roads with highway conditions. However, the sensitivity analysis exercises identified and quantified the influence of individual parameters on CALINE4 model’s output. The input parameters such as wind speed, wind direction, traffic volume and WEF were identified as influential parameters, which needs to be collected and estimated more accurately as compared to the other input parameters.

In a study carried out in heterogeneous traffic in Delhi (India) it was concluded that for input parameters like surface roughness and mixing height default values could be used (Dhyani and Sharma, 2017).

Such exercise help in bringing the focus only those influential input parameters (viz. wind speed, WEF, traffic volume) which affects the performance of the CALINE4 model. Similarly, the study identifies the input parameters which have insignificant influence on model’s prediction capabilities (viz., surface roughness, mixing height). As indicated above, sensitivity analysis exercise carried out on CALINE4 model suggested that, few input parameters in the model have more significance in the model’s output as compare to other input parameters. Thus, these exercised suggest a way to save the time and cost which goes in input parameters collection.
3.3 Input data requirement

The CALINE4 model is a simple in terms of its operations and requires less input data as compared to other Gaussian-based models viz., AERMOD and ADMS. The CALINE4 model requires following input characteristics:

1. Traffic data (hourly traffic volume, composition categorised according to fuel type and technology (two-wheelers, four-wheelers, trucks, buses, etc.), fuel type, etc. should be representative of the particular area or road corridor of concern.

2. Weighted emission factor [expressed in terms of gram/distance travelled (km or mile)] for different types and categories of vehicles, according to the vintage and fuel type of vehicle (Sharma et al., 2013).

3. Accuracy of meteorological data has significant relevance in the accurate predictions of concentration. Therefore, it is desirable to carry out on-site measurement of micro-meteorological data viz., wind speed, wind direction, temperature, stability class and mixing height.

4. Road geometry/characteristics of study corridors, which includes road length to be studied, elevation, road width, median width, orientation of the road. For each road link, specific source strength (traffic volume and weighted emission factor) needs to be provided due to any fluctuation in the traffic volume (addition or diverting) resulted from any merger or diversion of road/traffic.

5. Type of terrain plays significant role in the model, as it influences the meteorological parameters like, wind speed, wind direction, which influence dispersion of pollutants. Surface roughness of the site is based on the type of terrain in and around the selected corridor. CALINE4 model has option of selection of various terrains types (different surface roughness). Application of CALINE4 model is not advisable in complex terrain or hilly terrain (Benson et al., 1986; Dhyani et al., 2013)

6. Receptor locations – to predict air quality at sensitive receptors such as school, hospital or sensitive habitation (viz., wild life sanctuary, etc.).

7. Background concentration of pollutants – the background air quality includes pollutant concentrations due to:
   a. natural sources
   b. nearby sources other than the one(s) currently under consideration
   c. unidentified sources (MPCA, 2016).

Determining the source impacts is an essential part of the total air quality as it gives an overall picture of the air quality for further comparison with NAAQS. Further, comparing predicted and observed pollutant concentration is important for model performance evaluation as well as for its validation exercise.

3.4 Inadequacies in CALINE4 model

Models generally require various input parameters pertaining to meteorology, traffic, road geometry and land use pattern, besides receptor locations. Apart from the model’s own limitations, the non-availability of reliable and accurate input parameters poses
questions on the quality of the model’s output. Further, success of an air pollution dispersion model largely depends upon representativeness and accuracy of its input data describing the atmospheric characteristics (Elangasinghe et al., 2016). The non-availability of on-site meteorological data is a major factor of inaccuracy in CALINE4 model results.

Various researchers have discussed reliability, adequacies, limitations and associated uncertainties of these dispersion models. CALINE model cannot predict input wind speed less than 1 m/sec and take up speed 0.5 m/sec automatically as default value (Dhyani and Sharma, 2017). Benson et al. (1986) and Benson (1989) reported limitation of CALINE4 model under complex terrain conditions as the model assumes uniform horizontal wind flow and steady state meteorological conditions, which are difficult to achieve in complex terrain such as hilly region. Dhyani et al. (2013) evaluated and compared the performance of CALINE4 model for hilly and flat terrain and observed unsatisfactory performance of the model in hilly regions due to complex topography and micro meteorological conditions which could not be simulated properly in CALINE4 model.

Only a few studies have been done Gaussian-based street canyon models including CALINE series of model (Vardoulakis et al., 2003). Further, Holmes and Morawska (2006) reported that Gaussian models (e.g., CALINE4 and HIWAY-2) lack the sophistication required for modelling in a street canyon as a building can only be represented by changing surface roughness.

Akyurtlu and Akyurtlu (2012) applied the CALINE for prediction of NO\textsubscript{x}. The study observed that CALINE4 model over-predicted the NO\textsubscript{x} concentrations. Further, over-prediction indicates model’s inability to replicate the actual chemical reactions and conversion under given set of meteorological conditions.

In developing countries, the crude representation of traffic parameters (e.g., vehicle speed, queue length) are major limitations in the existing on-road vehicle emission estimations and air quality models, e.g., like CALINE4 (Lin and Ge, 2006). In CALINE4 model, emissions is presented by a single representative value of emission per vehicle (weighted emission factor) which ignores the traffic characteristics (homogeneous or heterogeneous) and does not present true traffic and emission conditions. Usually significant error occurs in the estimation of emission factors used for different categories of vehicles. Washington and Sperling (1994) concluded that when methodology for averaging emissions factor is applied to predict CO concentration, vehicle-to-vehicle emission variation is lost. Similar kind of averaging methodology is used in CALINE4 model in the form of weighted emission factors (WEF).

One of the major factors for the inaccuracy occurs due to unavailability of comprehensive and well-established emission factors for different categories of vehicles comprising vehicle fleet particularly in developing countries. During heterogeneous traffic conditions, variety of vehicles plies on the road with different engine capacity and emission behaviour. Due to a large variety of vehicles with different emission characteristics, engine capacity and fuel type within these broad categories these emission factors fails to justify the accuracy of these emission factors (CPCB, 2000). The problem gets compounded further as the emission factors database is not updated or keep up the pace with which vehicles with a wide range of engine and emission control technologies are added/introduced regularly in various categories of vehicles.

Another source of inaccuracy in the CALINE model pertains to model’s performance in varied meteorological conditions. CALINE4 assumes a steady state and uniform wind flow meteorological conditions (Benson et al., 1986; Benson, 1989) which are not true.
representation of prevailing atmospheric conditions. Modelling input data requirement is fulfilled from various field studies and estimations from secondary sources. Therefore, unreliable data or discrepancies while collecting and estimating input data can cause a considerable amount of inaccuracy in the predictions. As line source models, do not account for background concentrations therefore, it is not possible to compare model results directly with actual measured concentration (Marmur and Mamane, 2003).

According to Bluett and Fisher (2005), poor representation of meteorological conditions, vehicle numbers and correct assumptions for fleet composition are the important factors for good performance of the model. Later, Broderick and O’Donoghue (2007) while evaluating the ability of CALINE4 model for hydrocarbon emission (benzene) concluded that performance of model deteriorates with low wind speed and short-term performance of model in not good at receptors closest to the roadway.

Various researchers have also reported that CALINE4 model has been not been developed for analysis of turbulent propagation of non-reactive gaseous pollutant. Further, while predicting particulate matter CALINE4 model does not account for coagulation and nucleation (Benson, 1992; Gramotnev et al., 2003) leading to inaccurate predictions of particulate matter concentration. Therefore, before usage of model for air quality management plan one should be well versed with the features and its feasibility under specific site, traffic and meteorological conditions.

3.5 Usage of CALINE4 model for regulatory purpose

Vehicular pollution dispersion models are important tools in screening of vehicular exhaust emissions along the roads and highways (Sharma and Khare, 2001; Sharma et al., 2004). Gaussian-based dispersion model such as, CALINE4, AERMOD, CALPUFF, CAL3HQC, etc. most commonly use regulatory models which are been recommended by USEPA for use in estimating the concentration of non-reactive pollutants near highways (AustRoad, 2004). CALINE4 is often considered as a reference model against which various other atmospheric models are tested (Ganguly et al., 2009). Environmental impact assessment (EIA) studies of roads/highways corridors and decisions of regulatory agencies for future air quality management plan are often based on these model’s outputs. Future air quality area along the road corridors depends upon the performance of the air dispersion models used (in that area) for regulatory purpose. Similarly, modelling roadside concentrations for regulatory purposes or exposure assessment requires that the user be well aware of the model reliability and application domain (Malherbe et al., 2010). Level of accuracy in model’s input and its prediction capabilities makes it difficult to use it for regulatory purposes. Therefore, there is great importance in determining the accuracy levels of commonly used models (Marmur and Mamane, 2003).

4 Conclusions

Gaussian-based line source dispersion models viz., CALINE4 model has been used for regulatory purposes. Most of these models (including CALINE4 model) used in developing countries have been developed in western countries for their traffic and meteorological conditions. As discussed earlier, performance evaluation and sensitivity analysis studies carried out have indicated that source strength and meteorological
parameters like wind speed and wind direction have comparatively more influence on model prediction capabilities. In addition to that, thermal and vehicle induced turbulence are main factors that influences the dispersion of pollutants near the mixing zone width.

Further, various studies highlighted the model’s inherent limitations and discussed the inaccuracy in input data adds to uncertainty to model’s output. Thus, their role needs to be investigated further under heterogeneous traffic conditions.

It has been observed that although most of the studies CALINE series of model performed satisfactorily, but few comprehensive studies on model’s performance evaluation and validation have been done keeping varying (heterogeneous) traffic, climatic conditions.

Therefore, it could be concluded that in the absence of any general guidelines to evaluate the model’s performance under varying conditions, the focus area should be performance measures and sensitivity analysis of the model in changing terrain, meteorological and traffic situations bring further improvement in CALINE model’s prediction capabilities. In addition to that, CALINE4 model performance should explored for the prediction of pollutants like particulate matter (PM$_{2.5}$/PM$_{10}$), NO$_{2}$.

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