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Estimation of Automobile Emissions and Control Strategies in India

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Abstract:

Rapid, but unplanned urban development and the consequent urban sprawl coupled with economic growth have aggravated auto dependency in India over the last two decades. This has resulted in congestion and pollution in cities. The central and state Governments have taken many ameliorative measures to reduce vehicular emissions. However, evolution of scientific methods for accurate emission inventory is crucial. Therefore, an attempt has been made to estimate the emissions (running and start) from on-road vehicles in Chennai using IVE model in this paper. GPS was used to collect driving patterns.

The estimated emissions from motor vehicles in Chennai in 2005 were 431, 119, 46, 6 and 4575 tons/days respectively for CO, VOC, NO_x, PM and CO_2. It is observed from the results that air quality in Chennai has degraded. The estimation revealed that two and three-wheelers emitted about 64 percent of the total CO emissions and heavy-duty vehicles accounted for more than 60 percent and 36 percent of the NO_x and PM emissions respectively. About 19 percent of total emissions were that of start emissions. The estimated health damage cost of automobile emissions in Chennai is Rs. 6488.16 million (US$162.20 million). This paper has further examined various mitigation options to reduce vehicular emissions. The Study has concluded that advanced vehicular technology and augmentation of public transit would have significant impact on reducing vehicular emissions.

Key Words: Emission inventory; IVE model; GPS; emission reduction potentials; driving patterns; Chennai.

Introduction

Air quality in developing countries like India has reached an alarmingly high level. Most cities have exceeded the National Ambient Air Quality (NAAQ) standards. Particulate matter (PM) is a major concern in Indian cities and 60 out of 62 metropolitan cities have exceeded World Health Organization (WHO) standards. About 2.5 million premature deaths are caused annually due to PM exposure (Pandey et al., 2006). Two-wheelers and cars subscribed 78 percent and 11 percent of pollution load respectively in cities (Mahendra et al., 2005). Twenty percent of poorly

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maintained vehicles produce about 60 percent of vehicular pollution in India (Pundir, 2001). Main causes for the shocking increase in vehicular emissions have been the exponential growth in the number of motor vehicles; inadequate public transport and inept management; haphazard urban development; obsolete vehicular technology; laxity in traffic enforcement; and an increase in freight moved over roads (The World Bank, 2005; Badami, 2005; Pucher et al., 2005).

Insert Figure 1

Figure 1 shows that, as the number of cities grows, vehicle population and travel demand increases, driving up the amount of pollution as well. However, road length grows slowly. This significant disparity between demand and supply of transport infrastructure has caused severe congestion in all major Indian cities during peak hours. It has not only increased delays but also air pollution. According to Central Pollution Control Board (CPCB), city traffic adds about 2,000 tons of pollutants every day to the Delhi's air.

In recent years, the increasing contribution of the transport sector to greenhouse gas (GHG) emissions resulting from the use of fossil fuels, and their effects on global warming and climate change have been a major concern. It is estimated that there are about 900 million vehicles (excluding two-wheelers) worldwide that emit more than 26 percent of GHG emissions (Lee Chapman, 2007). In India, CO_2 emissions from the comsumption of fosil fuels have increased from 293 MMT to 1293 MMT between 1980 and 2006 (EIA, 2006). ADB projects the CO_2 emission from on-road transport in India will increase about 600 percent in next three decades (2005 – 2035) (ADB, 2006).

It is crucial to accurately estimate emissions. There are many emission models such as LEAP (Long-range Energy Alternative Planning), VAPIS (Vehicle Air Pollution Information System) and Spreadsheet models to estimate vehicular emissions. However, these models don't capture variations in local environments such as driving behaviors and traffic conditions. Further, these models are unable to assess the impact of traffic management schemes such as roundabouts, signal coordination, and road widening. These models also assume that lower vehicle speeds increase emissions. However, researchers have established that higher speeds can also increase or decrease emission if conditions are not steady (Anh K, et al., 2002). In addition, emission rates in these models are inadequate and fail to represent the latest vehicular technology.

To control vehicular emissions central, state and local governments have implemented many policy measures such as improving vehicular technology, revising traffic-management schemes, implementing stricter emission controls, introducing cleaner fuels, and promoting alternative fuels (CNG and LPG) . The effectiveness of such efforts has not been evaluated. Consequently,

the objectives of this paper are twofold: (i) to develop a methodology to estimate vehicular emissions accurately and (ii) to evaluate existing strategies to control vehicular emissions and recommend alternate strategies. The objectives could be achieved with credible database and sophisticated analytical framework. Research studies (Barth et al., 1997; Joumard et al. 1995; Sjodin et al., 1995) indicate that driving patterns significantly affect vehicular emissions. Therefore, in this study, global positioning systems (GPS) were used to collect driving patterns. Chennai city was selected for the case study.

Transport Characteristics of Chennai City

Chennai City is one of four metropolitan cities in India. It is located on the southeastern coast and reported in the 2001 census a population of 4.34 million people spread over 176 sq. km. The population density was 24,681/sq. km. Its economic base has ranged from utility service to automobiles. The city primarily depends on road transport and suburban rail services for intra-city commuting. The road network is in the form of radial pattern. N.H. 5 in the north, N.H. 45 in the southwest, and N.H.4 and N.H. 205 in the west radiate outwards from the Central Business District. Inner Ring Road and NH Bypass are other major corridors. The city has less than 10 percent of the space for roads and about 28 percent of road space is used for parking (WSA, 2008). Two-lane and four-lane roads account for 57 percent and 37 percent respectively.

Each household completes an average of about six trips per day, 56 percent for work, 23 percent for shopping, and the balance for other trips (Srinivasan et al., 2005). The pollutants per day from road transport in 2002 were 177 metric tons of carbon monoxide (CO), 95.6 metric tons of hydrocarbon (HC), 27.3 metric tons of oxides of nitrogen (NO_x) and 7.29 metric tons per day of particulate matter (PM) (GOI, 2002). Gasoline and diesel are the most common fuels in Chennai with a disproportionately higher share of diesel vehicles. On average, there were about 385 vehicles per 1,000 people in 2002. This was mainly due to rapid growth in the share of two-wheeled vehicles. An average of 425 new vehicles are added every day (CMDA, 2007). Table 1 describes the city's characteristics.

Insert Table 1

Methodology

The accuracy of emission inventory depends upon the availability of reliable local data such as the number of on-road vehicles, fleet characteristics, vehicle utilization, and driving patterns. These data are not readily available for Chennai City. Therefore, a primary survey was necessary. Surveys of driving patterns and a questionnaire were conducted to collect data. It is

not feasible to collect vehicle activity data in all areas of the city. Therefore, the city was broadly classified as Central Business District, Residential, and Industrial for the purposes of the study. Representative roads were selected.

The proposed methodology has three steps as illustrated in Figure 2.
  – Estimate the travel demand for different vehicle classes.
  – Assess the fleet composition of on-road vehicles.
  – Use the identified emission model to estimate accurate emissions.

Insert Figure 2

It is essential to know the number of on-road vehicles in order to estimate the travel demand. Vehicle registration data for different categories of vehicles were adjusted using the average lifespan in the absence of any data regarding the number of vehicles retiring from a road. Lifespan of different vehicles were defined as follows:
  • Two-wheelers - 15 years
  • Three-wheelers - 12 years
  • Automobiles, taxis, and SUVs - 15 years
  • Buses - 10 years
  • Goods vehicles - 15 years
[Mittal et al., 2000, Bose et al., 2002].

The estimated on-road population was multiplied by vehicle utilization to compute the travel demand as shown in equation (1).

$P_{it} = \sum V_{it} * U_{it}$ Eqn. (1)

Where, P - annual vehicle km traveled
V - Number of vehicles on road
U - Annual vehicle utilization (km)
i - Vehicle mode (car, TW, 3-wh, Bus and trucks)
t – Calendar year

On-road fleet characteristics are one of the important factors to estimate emissions. In this study, fleet characteristics were refined based on (i) the time series sales data of different technologies within a given mode; and (ii) the previous data collection by Central Road Research Institute and Pallavan Transport Consultancy Services. Fuel quality, temperature, and humidity were collected from the secondary survey.

The International Vehicle Emission (IVE) model is used to estimate accurate emission inventory in this study. IVE model was jointly developed by International Sustainable Systems Research Center and the University of California at Riverside through funding from the United States Environmental Protection Agency. This model calculates vehicular emissions at macro, meso, and micro scales. The IVE model can estimate emission inventory for local, global and toxic pollutants for the period of 1990 to 2050. It can estimate emissions from more than 700 different types of technologies with different combinations of fuel and after-treatment technologies.

It accounts separately for start emissions and running emissions. It also further considers changes in emission rates over time due to fleet turnover, diurnal emissions, hot-soak emissions, running losses, and refueling emissions. Base emission rates depend on vehicle technology, air/fuel ratios, engine sizes, and fuel types. The base emission rate data are collected from different locations such as U.S., Europe, China, India, and Thailand. It uses Vehicle Specific Power (VSP) and engine stress to capture the impact of driving behavior more accurately. VSP is estimated using speed, acceleration, and grade and it is shown in equation (2).

The IVE model estimates emission rates using equation (3) by adjusting for different correction factors. The general inputs to the model are fleet characteristics, vehicle activity, driving patterns, fuel quality, and temperature based on local conditions (IVE 2008, Davis et al., 2005).

$$VSP = v[1.1a + 9.81 (atan(sin(grade)))+0.132] + 0.000302v^3 \qquad \text{Eqn. (2)}$$
Where, VSP - Vehicle specific power

$\quad$ Grade = $(h_{t=0} - h_{t=-1})/v_{(t=-1 \text{ to } 0)}$

$\quad$ v - Velocity (m/s)

$\quad$ Acceleration (m/s^2)

$\quad$ h - Altitude (m)

$$Q[t]=B[t]* K(Base)[t]* K(Tmp)[t]* K(Hmd)[t]*K(IM)[t]* K(Fuel)[t]]* K(Alt)[t]]* K(Cntry)[t] * K(d)[t] \qquad \text{Eqn. (3)}$$

Where, $Q_{[t]}$ - Adjusted emission rate for each technology

$B[t]$ - Base emission rate in for each technology

K $(Base)$ [t] - Adjustment to the base emission rate

K (Tmp) [t] - Temperature correction factor

K (Hmd) [t] - Humidity correction factor

K (IM) [t] - Inspection/maintenance correction factor

K $(Fuel)$ [t] - Fuel quality correction factor

K$(Alt)[t]$ - Altitude correction factor

K$(Cntry)[t]$ - Country correction factor

K$_{[dt]}$ - Driving or soak style correction factor (Also accounts for other load effects from air conditioning usage and road grade)

Data Collection

Driving pattern is an important factor in estimating vehicular emissions. There are many methods to collect driving patterns including the chase-car technique, private drivers drive their own vehicles with instruments, private drivers drive instrumented vehicles, and private vehicles with instruments are driven by professional drivers (Andre 1996). We selected the latter method - private vehicles with instruments driven by professional drivers – for this study. Randomly hired local professional drivers drove instrumented vehicles. The drivers were familiar with the roads and local traffic rules. The purpose of the trip was not disclosed to drivers to avoid influencing their behavior. They were instructed to travel from a point A to point B to collect second-by-second traffic conditions. Drivers were also asked leave vehicles on at traffic lights, since the GPS units were powered through the vehicle's electrical system. Six vehicles of different makes, years, engine sizes, and weights and three handheld GPS units were used. GPS units were placed on the dashboards of vehicles to enable them to receive the best signal from the satellite as depicted in the Figure 3.

Insert Figure 3

Instrumented vehicles were driven in traffic flow to record second-by-second positional information and trajectory. Drivers either accelerated or slowed down their vehicles depending on traffic conditions. The instrumented vehicles represented all types of vehicles such as two-wheelers, three-wheelers, automobiles, and vans. Buses were excluded since they have different static and dynamic characteristics. Instruments were placed in buses operating along different routes with the special permission of the Metropolitan Transport Corporation (MTC) to collect the trajectory.

Data were collected in September 2004 during weekdays. There were no unusual conditions such as major processions, VIP visits, or other activities that could induce abnormal traffic characteristics in the selected corridor during the survey. Instrumented vehicles were driven during the morning peak (7:30–9:30 a.m.), afternoon off-peak (12:30–2:30 p.m.) and evening peak period (5–7:30 p.m.). Technicians noted street names, road surface characteristics, and causes for delays such as pedestrian crossings, incidence of parking, and turning vehicles. Data were generated for 276,000 seconds using cars and for 64,800 seconds using buses. Data were downloaded and the collected data were quality-checked for errors and inaccuracies. Driving patterns for different corridors were developed with the MATLAB program.

Questionnaire Survey:

A questionnaire was developed and a primary survey was conducted at five fuel stations in the study area to elicit opinion on vehicle utilization and starting patterns. Enumerators were trained on the conduct of the survey and appraised of the purpose and significance. The questionnaire was tested before data collection. The survey was conducted from 6 a.m. to 8 p.m. and about 495 usable samples were collected.

Information on average distance traveled per day, odometer readings, vehicle models, fuel types, fuel economy, number of starts per day, and off-time between starts were collected. Table 2 shows the vehicle utilization, fuel efficiency and number of starts for different vehicles. Start patterns are critical for emission inventory. Start emissions can be broadly classified as cold start and hot start**.** They depend on the number of hours vehicles are turned off. Cold starts emit higher CO and HC levels when the engine temperature is below 300° C. Studies indicate that a cold start consumes six times more fuel than a warm start (Baker, 1994). None of the previous studies have quantified the start emissions in India. Figure 4 shows the start time distribution of vehicles in Chennai.

Insert Table 2
Insert Figure 4

Emission Estimation Analysis

Based on this methodology, emissions were accurately estimated for local and global pollutants using the IVE model for 2005. The estimated emissions from motor vehicles in Chennai in 2005 were 431, 119, 46, 7 and 4575 tons/days respectively for CO, VOC, NO_x, PM and CO_2. About 19 percent of emissions are from start emissions. Figure 5 illustrates the estimated travel demand and source of emissions from different vehicle classes. Local pollutants are of immediate concern for urban air quality since they have significant impact on health. Temporal distribution of emissions are required to quantify the health impact of mobile source emissions in a city. Previous studies have quantified the temporal distribution based on traffic intensity and assumed the same for all pollutants. However, it varies based on many factors such as road geometry, traffic characteristics, and weather characteristics. Figure 6 shows the estimated daily temporal variation for different pollutants using IVE model. It can be seen that starts emissions are high during the morning peak hours.

Insert Figure 5
Insert Figure 6

In Chennai, about 64 percent of the total CO emissions are contributed by two and three-wheelers, which primarily use two-stroke engines. Stringent emission norms have reduced emissions per vehicle over the last decade but the number of vehicles has increased dramatically during the same period. About 18.2 percent of total CO emissions are emitted during the start-up. Gasoline vehicles alone contribute about 88 percent of VOC emissions. This is mainly due to lower combustion efficiency in gasoline engines, more specifically in two-stroke engines. It has been estimated that 15-25 percent of two-stroke engine exhaust is unburned fuel (Pundir 2001). In Chennai, 26 percent of VOC emissions are due to start-ups.

Heavy-duty vehicles (buses and trucks) contribute more than 60 percent and 36 percent of the NO_x and PM emissions respectively. The emission rate of NO_x is higher in diesel heavy-duty vehicles because of lower combustion temperatures. A recent study observed that the ground-level ozone in Chennai has reached 53 ppb, which is unhealthy for sensitive groups (Pulikesi et al., 2005). Currently, about 11 percent of PM are from start-up emissions. Private vehicles are a large and growing source of CO_2. Recent statistics show that overall fuel consumption within the transport sector in India is increasing. Regardless of emission control, CO_2 emissions from the combustion of gasoline and diesel remain roughly constant.

Cost of Automobile Emissions

The impact of automobile emissions can be better understood in terms of health damage. In India, very few studies have been conducted to quantify the cost of health damage resulting from air pollution. Recently, a study by Sengupta et al., (2005) attempted to quantify the unit cost of criteria pollutants from on-road transport for 35 Indian cities. They adjusted estimated U.S. costs for Indian context. Their adjustments included the difference in purchasing power, variation in the income levels, differences in population density, and inflation. They provided the lower and upper limits of the cost estimates as shown in Table 3. In this study, the median value of the per-unit cost of health damage for different pollutants was multiplied by the annual emissions of the respective pollutants. This translates to Rs. 6488.16 million (US$162.20 million)[2].

Insert Table 3

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[2] Conversion used US$1 = Rs. 40.

Strategies to Control Automobile Emissions

The emission inventory analyses clearly establish that air quality in Chennai has degraded. The following three strategies have been identified to reduce local and global pollutants in Chennai. Each strategy is discussed in detail with reference to Chennai.

1. Reduction of vehicle kilometer traveled (VKT) through transit-oriented development and travel demand management (TDM).
2. Adoption of advanced technology (vehicles, fuel and I/M program)
3. Transport system management (TSM).

Reduction of VKT through Transit-Oriented Development :

The average trip length in Chennai has increased from 6 km to 8 km mainly due to urban sprawl over the last two decades. Total daily person-trips in Chennai are projected to increase from 10.6 to 20.8 million in next two decades (CMDA, 2007). Therefore, the Chennai Metropolitan Development Authority (CMDA) plans to intensify development along transit corridors through increased FSI (floor space index) and relaxed parking regulations. Higher urban density can significantly reduces VMT and increases the share of transit use. A study by Johnston et al., (1998) ascertained that intensifying transit corridors can reduce emissions by about 5 percent and decrease travel costs. Another study demonstrated that transit-oriented development increases transit ridership about 30 percent and reduces about 1.7 personal vehicle trips per household per day (Cambridge Systematic et al., 1996).

Reduction of VKT through Travel Demand Management (TDM) :

The modal shift from private vehicles to public transportation can significantly reduce VKT. Chennai City has 3,000 buses that cater to 4 million passenger trips per day. The city has four rail corridors with a combined length of about 140 km and that carry about 0.7 million trips per day (Subramanian, 2008). The modal split between public and personal transport (share of modes) has been about 35:65. However, SMP has ambitiously proposed to increase the share of public transport from 35 to 70 by 2026 with a sub-modal split of 60:40 between bus and rail. This could be possible only through radical and far-reaching decisions.

Traffic management in Chennai focuses on TSM such as one-way streets, turning restrictions and traffic control devices completely ignore TDM. The underlying principle of TDM is to restrain extravagant use of low-occupancy private cars and two-wheelers. The techniques could be parking control, tolls, road pricing, motorist traffic restraint, and staggering office and school hours. A study found that a 5 percent increase in public transit share reduces VMT about 8 percent in 25 years and 12 percent in 50 years (Johnston et al., 2005). Pratt (1999) proved that a 1 percent increase in transit operation increases ridership .5 percent.

The Mass Rapid Transit System (MRTS), the first of its kind in the country, was extended to about 20 km during 2007 in Chennai. Fleet strength of the MTC was substantially augmented, for the first time in 30 years. A further expansion, through JNNURM (Jawaharlal Nehru National Urban Renewal Mission) funding, is under consideration. However, mere promotion of public transport (PT) is inadequate to shift commuters to PT from personal transport. Simultaneous disincentives for private vehicle use are required to achieve increased ridership. Increasing the costs to operate private vehicles by 75 percent and decreasing the cost of transit fares by 50 percent could reduce GHG emissions and fuel consumption by 10 percent. Therefore, adoption of TDM techniques is a crucial emission-control strategy.

Advanced Technology:
Developing advanced technology to meet stringent standards may be a better way to reduce vehicular emissions. Bharat Stage I, II, and III were introduced in 2000, 2001, and 2005 respectively for four-wheeled vehicles in Chennai. Bharat Stage IV is expected to be implemented in 2010. Bharat Stages I and II were introduced during 2000 and 2005 respectively for two- and three-wheelers and are the most stringent norms worldwide.

Fuel quality must align with advanced technology to meet stringent emission standards. Sulphur content in fuel is the most important factor and has a drastic impact on emission-control technologies. Table 4 indicates the required sulphur content to meet the different levels of stringent emission standards. Fuel injection technology with a two-way oxidation catalyst must be used to meet the Bharat Stage III standards in two- and three-wheeler segments (Iyer et al., 2007).

Insert Table 4

Battery-powered cars and hydrogen-fuel-cell buses are alternative technologies to significantly reduce local and global pollutants. However, the cost of such technologies is beyond the affordability of most road users in India. In developed countries like the U.S., these technologies are at demonstration stages and mass production is not expected until beyond 2025-2030 due to performance limitations and safety requirements (Walsh et al., 2007). In Chennai, the Department of Transport has introduced about 5,000 liquefied petroleum gas (LPG) -based three-wheelers to promote alternative-fuel vehicles (CMDA, 2007). Such technologies could be adopted at ecologically sensitive areas in a limited way.

It has been well-established that properly designed and operated inspection and maintenance (I/M) programs can significantly reduce vehicle emissions. A study in Phoenix to evaluate the

long-term benefits of I/M program found a 3 percent reduction in CO, a 6 percent reduction in HC, and a 7 percent reduction in NOx emissions (Wenzel 2001). In Chennai, there is no full-fledged I/M program. However, there is a mandatory requirement for all vehicles to undergo a Pollution Under Control (PUC) check every six months. There are about 66 Emission Test Centers in the city. Most are located at fuel-filling stations. Because of lax enforcement, only 10 percent of vehicles undergo the mandatory PUC which is ineffective in identifying the major polluters (Zubeda, 2007).

Traffic Management:

Sound management principles coupled with modern technology play crucial roles in improving traffic flow and road safety without impairing environmental quality. However, traffic management in Chennai is marked by inefficiency, driver non-participation, and corruption. Use of modern techniques is still in its infancy. Traffic control devices are outdated. They are inappropriately placed, inconsistently operated, and improperly maintained. Road markings do not retain their legibility and visibility. Nesamani et al., (2006) found that average speed in Chennai city is less than 20 kmph during peak hours.

Parking is the most challenging problem in Chennai. Commuters do not normally pay parking fees. Shoppers either indiscriminately park wherever they find space and pay (or ignore) a nominal fee. The city has about 5,100 passenger car equivalency (PCE) compared to 13,000 PCE during rush hour (CMDA, 2007). Vaca et al., (2005) found that a 10 percent increase in parking charges can reduce 3 percent of VMT. In California, levying US$3 reduced 3 percent of vehicles trips, 7 percent of delays, and about 3 percent of vehicular emissions (Harvey et al., 1996). Another study by Kupman et al., (1999) found that a monthly parking fee of US$20 may shift 10-30 trips to other modes such as mass transit and carpools. Therefore, hefty parking tariffs should be levied to discourage personal modes.

Scenario Design

Scenarios are developed to address the complexity and uncertainty in forecasting the outcomes. To develop these scenarios, the author analyzed historical data and examined various options and strategies. Three scenarios were developed to assess the emission-reduction prospects of policies in Chennai. The impact of the identified strategies was quantified for 2005–2025. Scenarios in this analysis are based on different stages of development in reducing VKT, penetration of advanced technology, and traffic management. This will guide policymakers to develop and implement better initiatives.

Business-as-Usual (BAU) Scenario:
In BAU scenario, it is assumed that vehicular growth will continue as expected. Further, this will capture the change in modal split, technology penetration, and utilization of vehicles. All new vehicles will meet Bharat Stage emission norms as based on current policy measures. However, it assumes there are no considerable changes in transport or environmental policies. This is the reference case for comparison purposes.

Intermediate (IM) Scenario:
The travel demand for passengers and goods will follow the same growth curve as in BAU. However, this scenario allows for greater changes by considering earlier penetration of advanced technologies, increasing the share of mass transit, and introducing traffic management schemes to feasibly reduce VMT.

Enhanced (EH) Scenario:
The third scenario includes feasible/expected policies and also strategies that will be difficult to implement. The assumptions are similar to the IM scenario, but the penetration of advanced technologies and modal shift toward public transport will be earlier than in IM. This scenario considers maximum options to reduce local and global emissions from vehicles, which can be implemented by aggressive government initiatives and people's participation.

Scenarios portray the range of future possibilities and illustrate the scale of options needed to restrain growth in vehicle use, local pollutants, and GHG emissions. The IVE model was used to evaluate these three scenarios in which it was assumed that driving patterns and start time distributions would be the same as in 2005. Table 5 suggests policies to reduce emissions and each scenario is built on the previous one, but assumes progressively faster changes.

Insert Table 5

Table 6 shows the change in modal split among different scenarios. In the BAU scenario, the share of public transport decreases from 36 percent in 2005 to 29 percent in 2025. It is projected that 70 percent of passenger travel demand will be met by public transport in 2025 (including MRTS) in an enhanced scenario. This can be achieved by doubling the density along the MRTS corridor, increasing the frequency and comfort of public transit, introducing congestion pricing, and increasing parking charges. The emission estimation analysis is for on-road transport only and does not include the rail system. The expected increase in rail system usage will obviously reduce the total on-road travel demand.

Insert Table 6

New technologies within each mode must be the state of the solutions to meet stringent emission norms. This is based on discussions with industry experts and on government plans and programmes for introducing new technology-based vehicles to improve air quality. Table 7 gives the penetration of improved technologies under the private, IPT, and public transport modes during 2005-2025 in the city.

Insert Table 7

Policy Evaluation

Travel Demand
Travel demand for passenger and freight vehicles was estimated for 2005-2025 with 10-year intervals using the Equation 1. The share of vehicle travel demand provided by different modes is shown in Figure 7. The total VKT in Chennai is expected to double before 2015 and increase 5 times by 2025. The annual growth rate of private vehicles is predicted to be about 21 percent between 2005 and 2025. This rapid growth is attributable to an increase in per capita income, increased access to personalized vehicles, and greater distances traveled. The number of buses is less than 1 percent of vehicles, which caters to about 35 percent of the passenger travel demand. However, in the future, it is expected to reduce to 29 percent by 2025. The total freight demand in the city went up 6.4 percent annually from 2005 - 2025.

Insert Figure 7

The impact of different policies on vehicle travel demand in 2025 in different scenarios is illustrated in Figure 8. The share of private vehicles has declined by about 32 percent and 60 percent in intermediate and enhanced scenarios compared to the BAU scenario. On the other hand, the share of public transit increased about 42 percent and 71 percent in an intermediate and enhanced scenario respectively to meet the growing demand in the city. The major factors that significantly reduced the travel demand in an enhanced scenario were due to densification of MRTS corridors and augmenting the public transport.

Insert Figure 8

Emissions
Figure 9 illustrates the estimated emissions for three scenarios using the proposed method. The rate of increase has reduced for all the pollutants; however, the total emission load increased compared to the 2005 level. In the BAU scenario, local pollutants dropped from 601 tons/day to

583 tons/day in 2015 and increased again to 758 tons/day in 2025. In the case of global pollutants, there was a steep increase in emissions from 4,575 tons/day to 14,954 tons/day in 2025, which might be due to rampant growth. This indicates that the proposed policies have only a short-term effect on emissions and growth in demand supersedes the benefits. On the other hand, intermediate and enhanced scenarios show a reduction in pollutants of 19 percent and 38 percent in next two decades respectively. This is due to strategies such as penetration of advanced technology and traffic management schemes. This indicates that there is a potential to reduce emissions in Chennai.

Insert Figure 9

The impact of different policies on each pollutant has been analyzed in detail. The intermediate and enhanced scenarios reduced CO emissions by about 21 percent and 37 percent respectively in comparison to the BAU scenario. This is mainly due to increased use of public transit and an effective I/M program. In the enhanced scenario, HC reduced about 40 percent over 20 years. These changes are because a substantial share of personalized vehicles are expected to shift toward alternative fuels. NOx emissions drop below the 2005 level in 2025 in the enhanced scenario, mainly due to the penetration of new and efficient technology, and the replacement of older, heavy-duty trucks.

PM emissions would increase more than two times over the next two decades if existing trends continue. The phasing out of diesel vehicles and introduction of atertreatment technologies have reduced 20 percent and 49 percent of PM emissions in the intermediate and enhanced scenarios respectively. Under the intermediate scenario, CO_2 emissions increase and the rate of increase starts falling gradually later. Even in the enhanced scenario, CO_2 emissions increase primarily due to high growth rates in total VKT. This suggests that this might be due to insufficient penetration of fuel-efficient and clean-fuel vehicles.

Discussion and Conclusions

This paper has formulated a methodology to estimate vehicular emissions accurately using GPS data. This study has quantified both local and global pollutants using the IVE model. Further, it analyzes the implications of various policy options for reducing vehicular emissions under three alternative scenarios in Chennai City. This study concludes that, under the ongoing economic growth in Chennai, aggressive efforts are required to reduce vehicular emissions. Central, state, and local governments should adopt following measures:

(i)   Enhance and extend public transport infrastructures
(ii)   Accelerate the adoption and deployment of improved technology

(iii)   Deploy effective I/M programs

(iv)   Implement optimized programs for traffic management and enforcement

Existing services and amenities should be improved by increasing service frequency, reducing headways, improving service reliability, adding bus shelters, properly designing traffic control devices, and improving safety and cleanliness. Existing fare and pricing strategies should be changed to support innovative methods such as transfer policies and partnerships with businesses or other institutions to provide discount fares. Train and bus services compete with, rather than complement, each other. They should be integrated with in the ambit of public transit agency as a first step and later integrate with private modes.

India should reduce sales taxes and import duties through incentives to encourage faster penetration of advanced technologies such as hybrid vehicles, BOV, and fuel cells. It is necessary to improve the fuel quality to take advantage of after-treatment technologies such as particulate traps and catalytic converters. Since the Indian transportation sector consumes more than 90 percent of HSD, it is imperative to reduce the sulfur and benzene content in diesel fuel all over India. Recently it has been permitted to use ethanol blend up to 5 percent in gasoline (GOI 2002).

A major contributor to air pollution is improper maintenance of vehicles and the operation of older vehicles. I/M programs have reduced about 5-11 percent of different pollutants in an enhanced scenario (in comparison to BAU). This strongly indicates a need for a proper inspection and maintenance program for in-use vehicles. In India, there is no statutory restriction on the number of years a vehicle can be on road. It is, therefore, important to encourage early replacement of older vehicles through incentives. Statuary age limits and compulsory inspections for all vehicles should be passed under Central Motor Vehicle Rules.

Traffic management strategies have improved the average speed in the city. This has reduced 5 percent of total emissions in an enhanced scenario in comparison to BAU. This indicates that traffic management schemes have long-term positive impacts on emissions and are as effective as other policies. Revenues from this strategy can be used to improve public transit services in Chennai.

Extensive application of technology and minimizing human interactions in enforcing regulations are reliable ways to improve the situation. A vital aspect of enforcement is the manner in which individual police behave while enforcing traffic rules. Violators should not be treated on par with criminals and offenders. Perhaps traffic management responsibilities should be shifted from the police and entrusted to a dedicated traffic-management team.

Acknowledgements

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List of Tables

Table 1 Transport Characteristics of the City

City population (2001)	4.22 million
Area	174 sq. km
Population density	24,231 persons per sq. km
GDP per capita	
Number of registered vehicles	1.5 million
Modal split[1]	Private vehicles – 30% IPT – 8% Public transport – 31% NMT – 31%
Fare (Rs.)	Bus – 2.00 (USD 0.04) Rail – 4.00 (USD 0.08)
Annual fuel consumption (2001) [2]	Diesel – 298 TMT Petrol – 152 TMT
Speed limit	Cars and two-wheelers – 40 km/hr Three-wheelers and buses – 25 km/hr
Road length	4179
Average trip length	8.6 km
Trip rate (2008)[1]	1.5 (all modes) 1.02 (motorized)
Number of motor vehicle accidents (2005)	4499

[1] WSA, 2008.
[2] Sengupta, 2005.

Table 2 Average utilization and fuel efficiency of different vehicles

Mode: fuel	Vehicle Utilization (km)	Fuel efficiency (km/Liter)	No. of starts (per day)
2-wheeler: petrol	21	48.8	9.1
Car: petrol	30	10.1	7.8
Car: diesel	30	9.5	7.8
3-wheeler: petrol	85	21.5	14.4
Taxi: gasoline	98	10.5	10.8
Taxi: diesel	98	10.1	10.8
Bus: diesel	186	3.5	11.7
Light commercial vehicles: diesel	45	8.6	6.7

Table 3 Health Damage Cost of different pollutants in Chennai

Cost (Rs./kg)	CO	VOC	NO$_x$	PM
Lower bound	0.01	0.17	2.04	17.67
Upper bound	0.13	1.86	30.02	241.13
Median	0.07	1.02	16.03	129.4

Source: Sengupta et al., 2005.

Table 4 Implementation Date of Bharat Stage norms and permissible sulphur level in fuel specifications for different category of vehicles in Chennai

Modes	Effective date of mass emission standards				Fuel specification – maximum Sulphur % (w/w)			
	BS-I	BS-II	BS-III	BS-IV	BS-I	BS-II	BS-III	BS-IV
4-wheelers	April/2000	April/2001	April/2005	April/2010	0.1 (gasoline) 0.25 (diesel)	0.05 (gasoline and diesel)	0.015 (gasoline) 0.035 (diesel)	0.005 (gasoline and diesel)
2 & 3 Wheelers	April/2000	April/2005	April/2008 - April/2010	--	0.1 (gasoline) 0.25 (diesel)	0.05 (gasoline and diesel)	0.015 (gasoline) 0.035 (diesel)	0.005 (gasoline and diesel)

BS - Bharat Stage norms.

Source: GOI, 2002; SIAM, 2008.

Table 5 Policy options to control automobile emissions under different scenarios

Policy Options	Business-as-usual (BAU)	Intermediate (IM)	Enhanced (EH)
Reducing Vehicle Kilometer Traveled	− The share of public transport will continue with existing trend.	− 50 percent of passenger travel demand will be met by public transport (2.4 million VKT by buses).	− Doubling the density along the MRTS corridor which will reduce 3 percent of travel demand. − Modal split between public and private transport will be 70:30 (about 3 million VKT by buses).
Advanced Technology	− Penetration of new vehicles conforming to Bharat Stage norms. − 5 percent of vehicle travel demand will be met by alternative fuels.	− Penetration of new vehicles conforming to Bharat Stage norms. − 10 percent of vehicle travel demand will be met by alternative fuels.	− Earlier start date for the penetration of advanced technologies. − 10 percent of vehicle travel demand will be met by alternative fuels. − 5 percent of vehicle travel demand will be met by zero emission vehicles. − Introduction of effective inspection and maintenance program for in-use vehicles. − Replace pre-2000 trucks with better aftertreatment technologies (particulate traps).
Transport System Management	− Introduction of hefty parking charges for 2- and 3-wheelers in commercial areas.	− Introduction of parking charges for work trip which will reduce 1 percent of vehicle travel demand.	− Introduction of congestion pricing and increasing the parking charges which will reduce 3 percent of vehicle travel demand.

Table 6 Change in modal split between scenarios

Mode	Business-as-usual			Intermediate			Enhanced		
	2005	**2015**	**2025**	**2005**	**2015**	**2025**	**2005**	**2015**	**2025**
Private	54.6	60.7	66.7	54.6	53.0	46.7	54.6	44.0	28.0
IPT	9.8	5.2	4.2	9.8	4.2	3.3	9.8	3.2	2.0
Public	35.6	34.1	29.1	35.6	42.8	50.0	35.6	52.8	70.0

Table 7 Penetration of technologies by mode under alternative scenarios

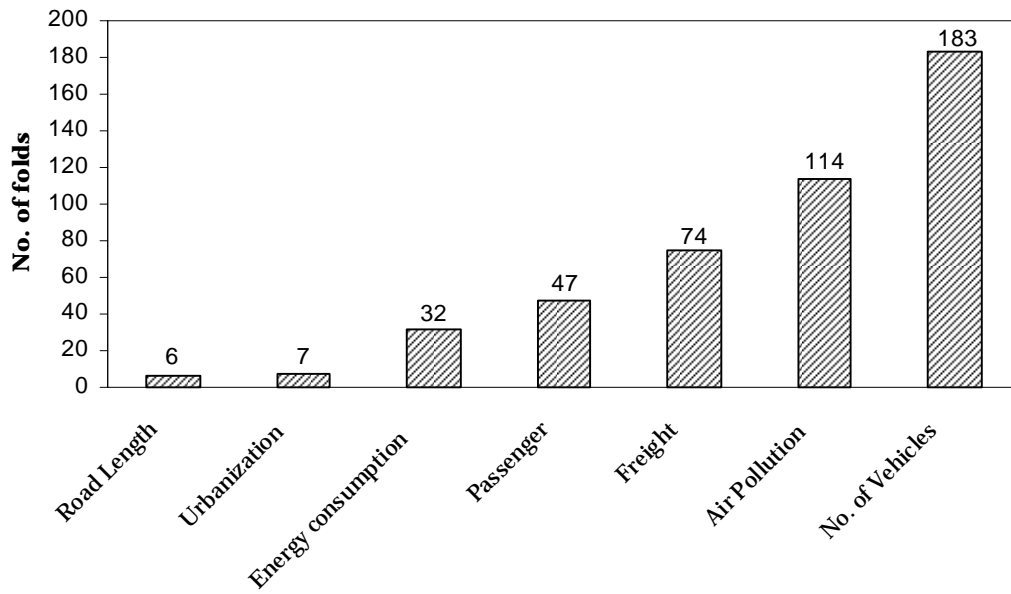| Mode: technology: fuel	2005	2025		
		BAU	**Intermediate**	**Enhanced**
2-wheeler: 2 stroke petrol	85	70	40	0
2-wheeler: 4-stroke: petrol	15	30	60	100
Car: gasoline	74	60	35	0
Car: diesel	24	23	15	0
Car: LPG	2	17	35	50
Car: hybrids	0	0	15	40
Car: BOV	0	0	0	10
3-wheeler: 2-stroke: petrol	90	50	10	0
3-wheeler: 4-stroke: petrol	10	20	30	0
3-wheeler: LPG	0	27.5	60	87.5
3-wheeler: BOV	0	0	0	12.5
Taxi: gasoline	30	25	10	0
Taxi: diesel	70	50	20	0
Taxi: LPG	0	25	70	80
Taxi: BOV	0	0	0	20
Bus: diesel	100	100	97	92
Bus: FCV	0	0	3	8
Goods	100	100	100	100

List of Figures

Figure 1 Number of times the infrastructure, vehicle population, energy consumption, and travel demand have grown during the last five decades (1951 – 2000) in India.
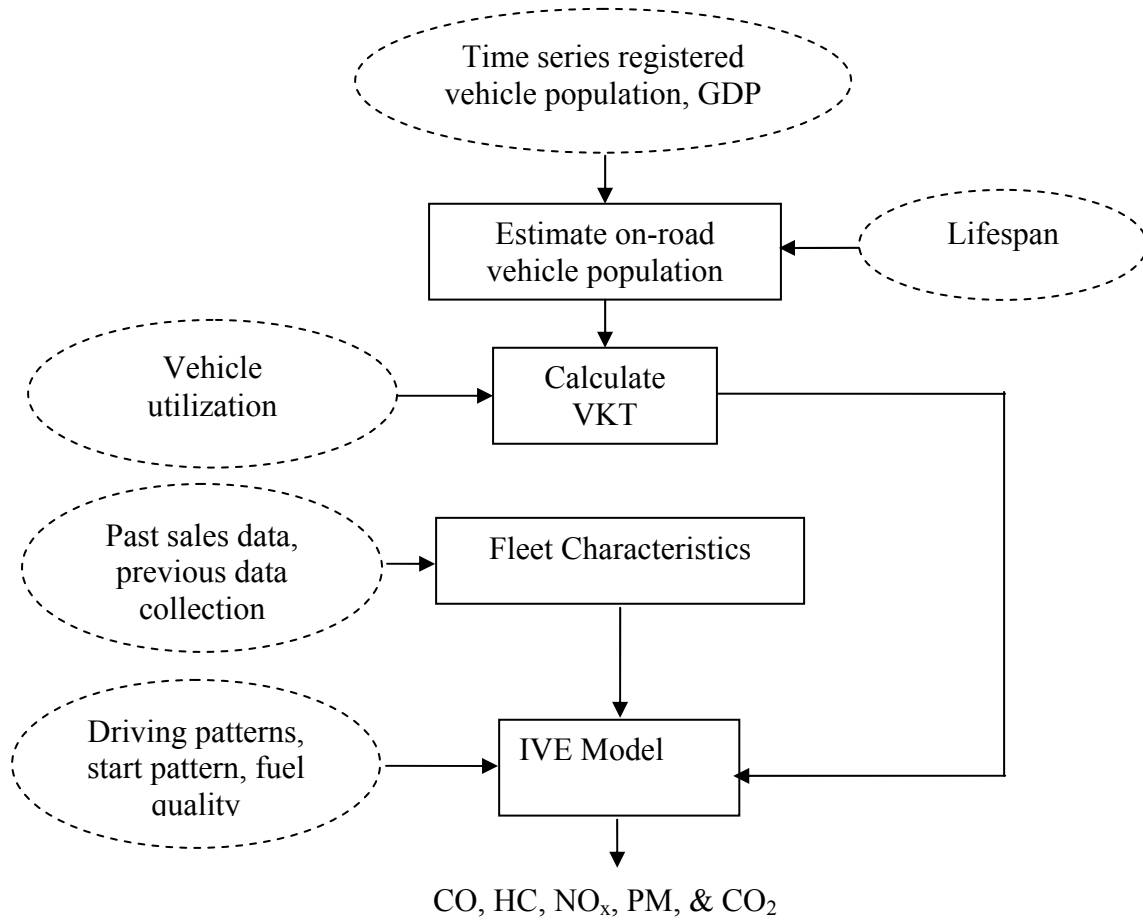
Figure 2 Methodology to estimate vehicular emissions
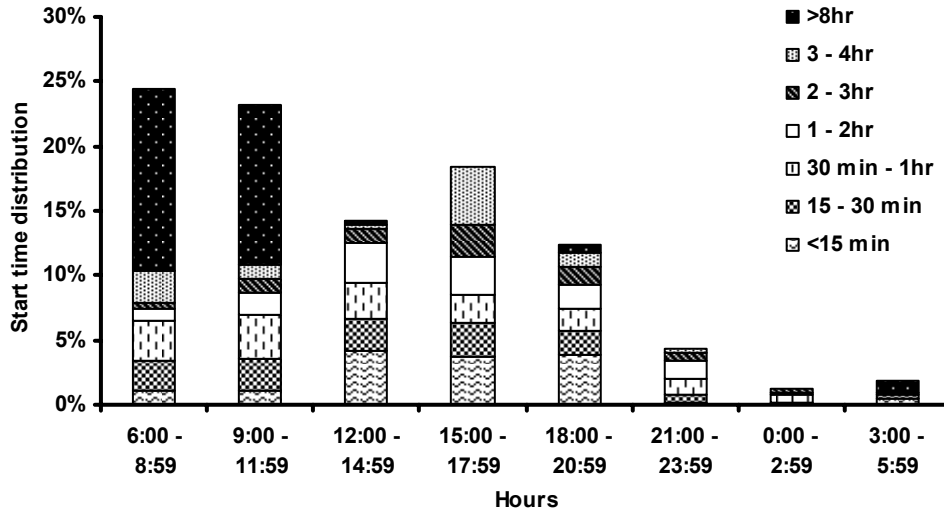

Figure 3 GPS unit in a test vehicle

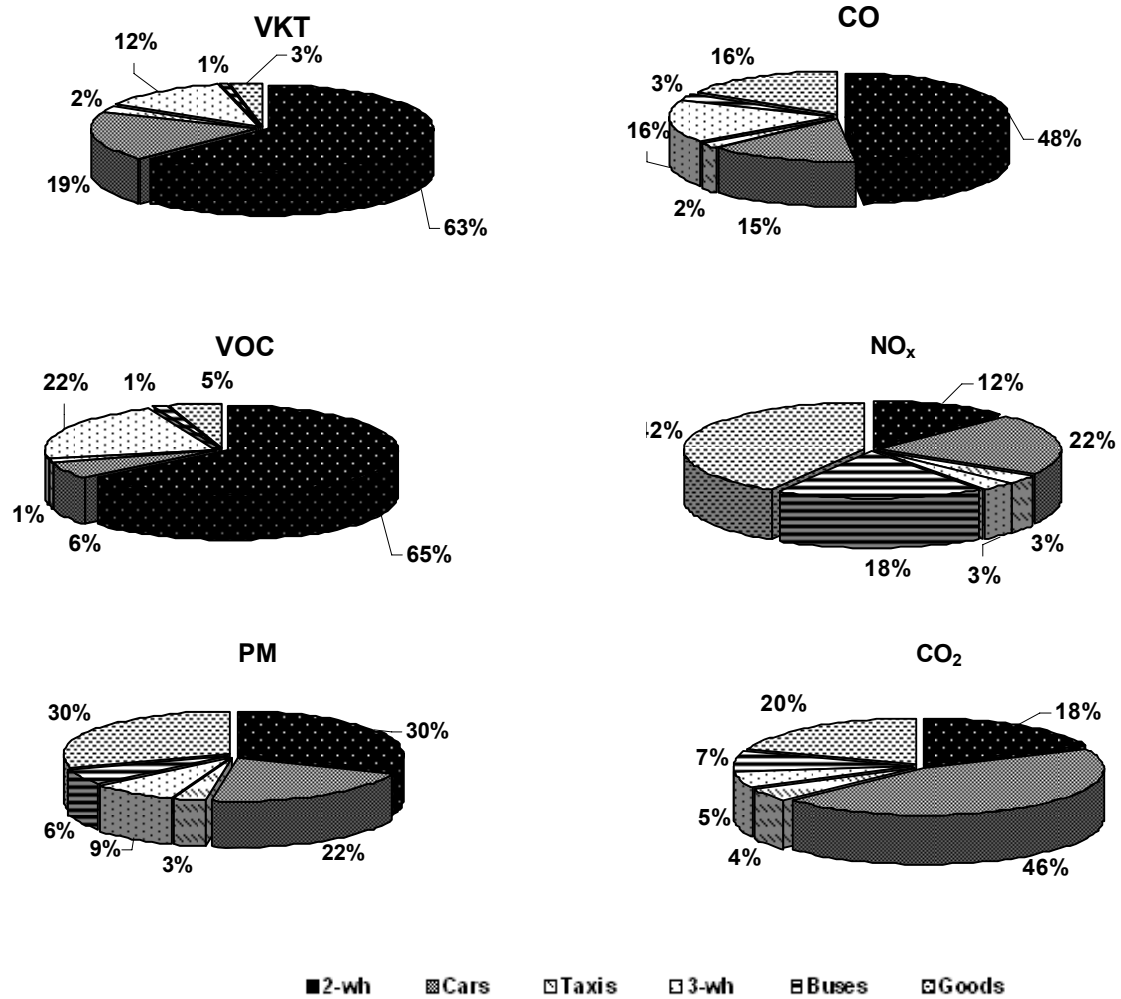**Figure 4 Soak time distributions of vehicles in Chennai**

VKT

- 12%
- 2%
- 19%
- 1%
- 3%
- 63%

CO

- 16%
- 3%
- 16%
- 2%
- 15%
- 48%

VOC

- 22%
- 1%
- 1%
- 6%
- 5%
- 65%

NO$_x$

- 2%
- 12%
- 22%
- 3%
- 3%
- 18%

PM

- 30%
- 6%
- 9%
- 3%
- 30%
- 22%

CO$_2$

- 20%
- 7%
- 5%
- 4%
- 18%
- 46%

■2-wh   ▩Cars   ▨Taxis   ▢3-wh   ▤Buses   ▥Goods

Figure 5 Estimated emission from different vehicle classes

29
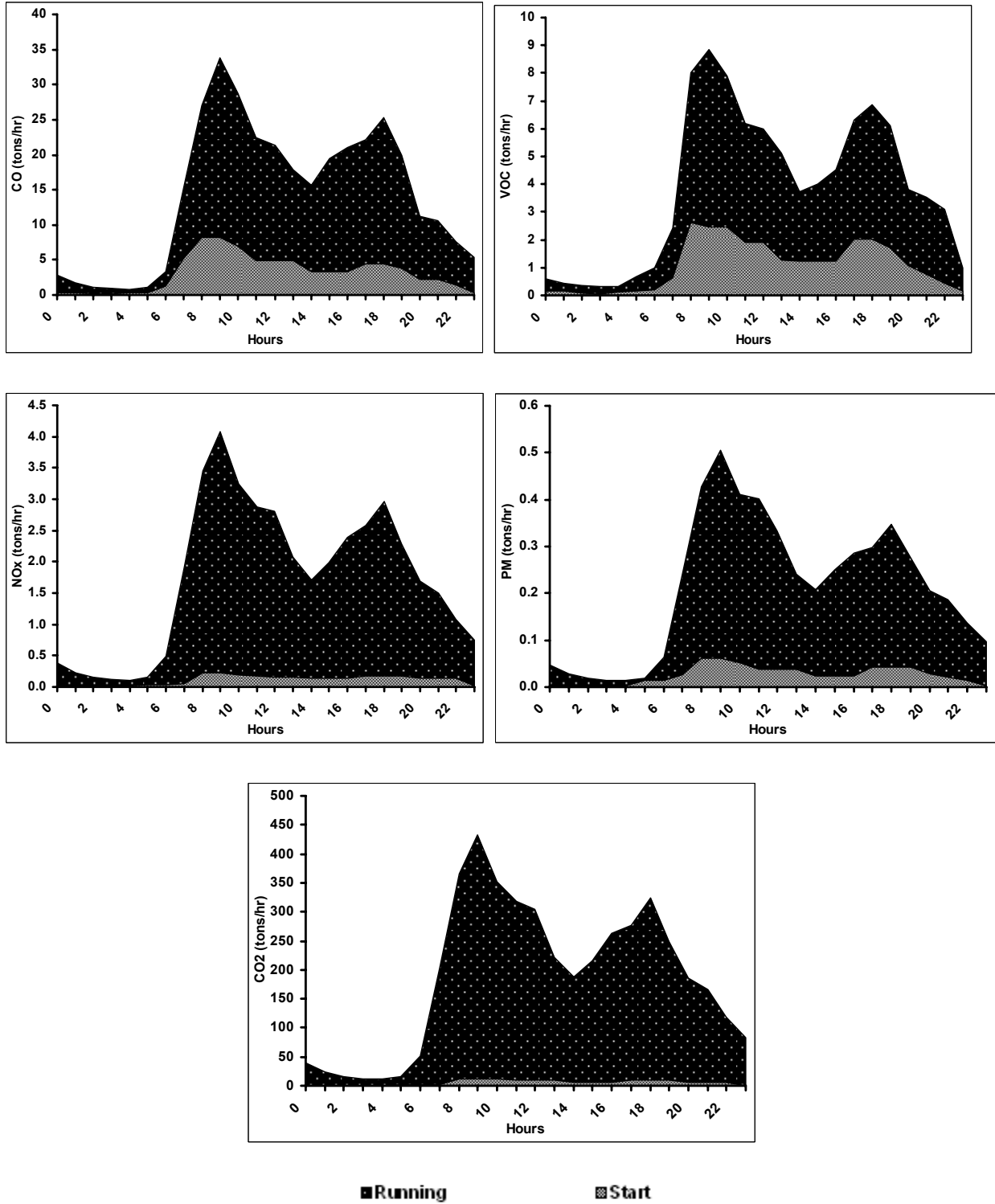
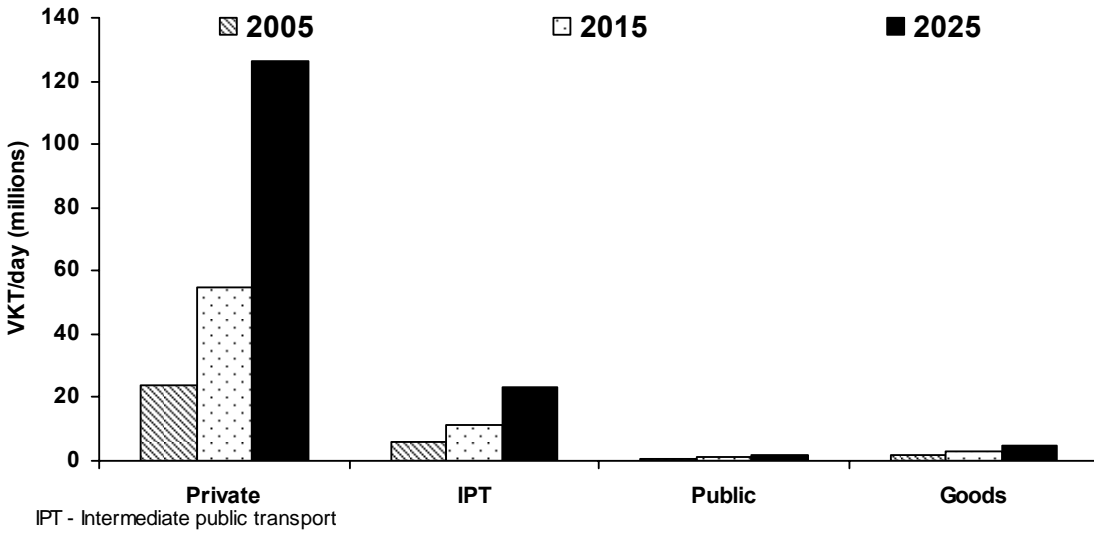**Figure 6 Temporal variations of mobile source emissions in Chennai City**

Figure 7 Estimated vehicle travel demand by different modes
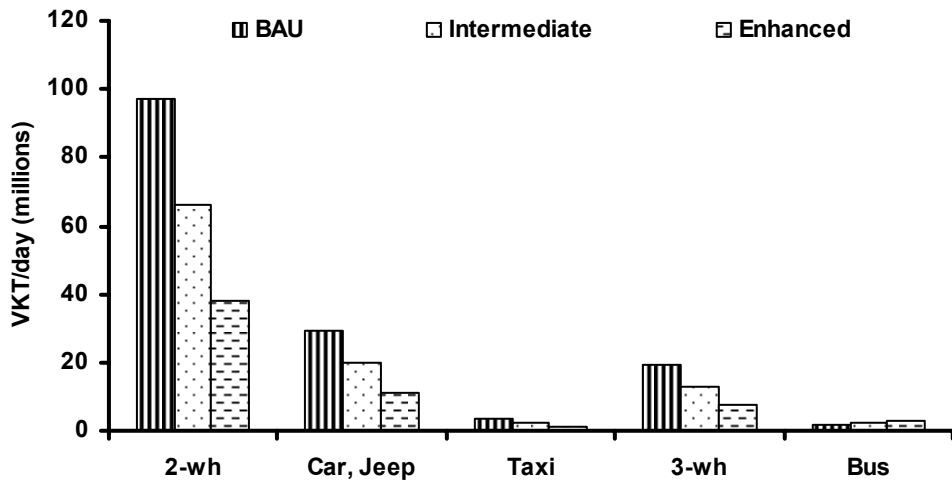

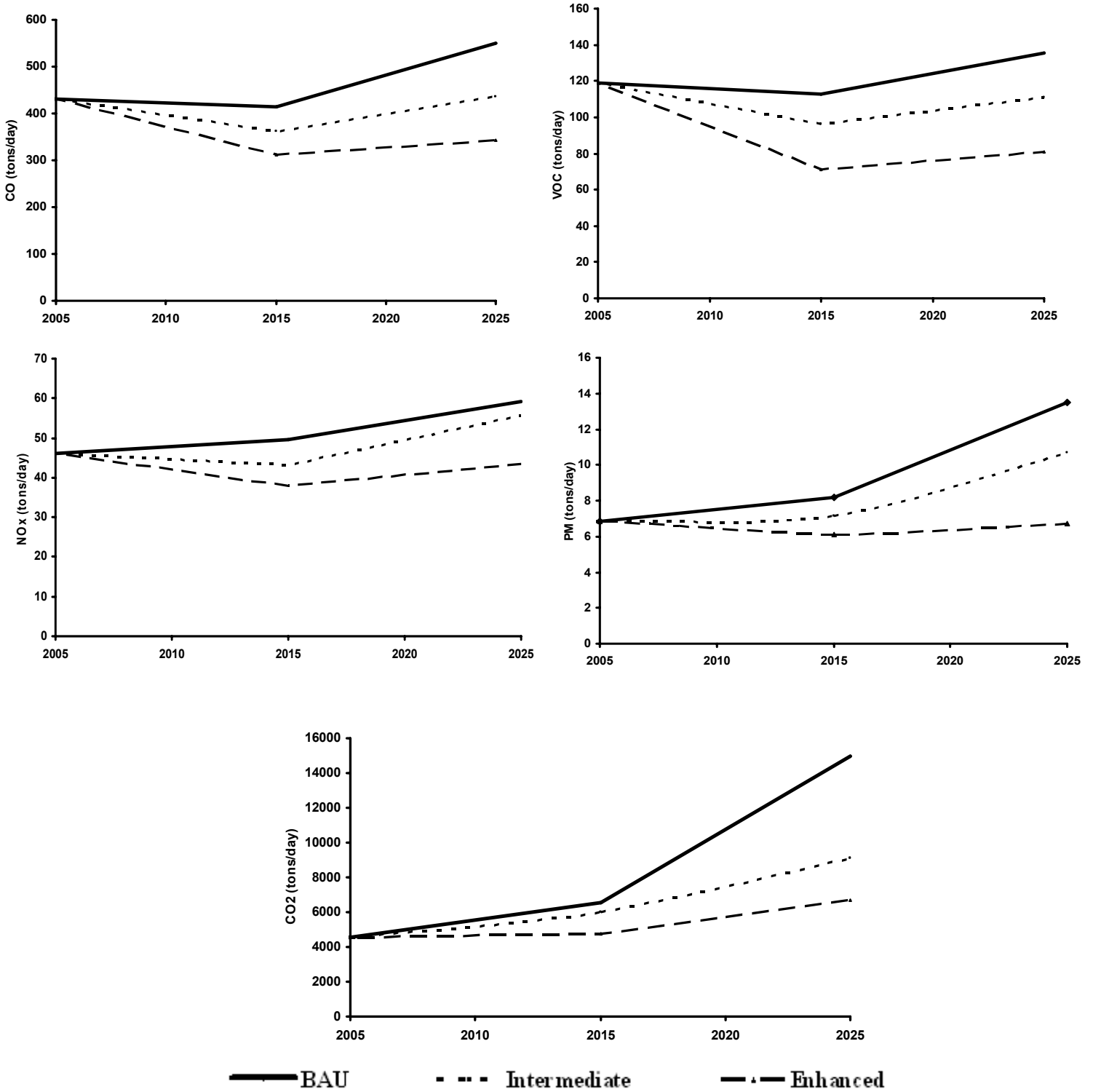**Figure 8 Share of travel demand by different mode in 2025 in different scenarios**

Figure 9 Estimated emissions under different scenarios