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# Impact of Real-World Driving Characteristics on Vehicular Emissions*

K.S. NESAMANI** and K.P. SUBRAMANIAN***

With increase in traffic volume and change in travel related characteristics, vehicular emissions and energy consumption have increased significantly since two decades in India. Current models are not capable of estimating vehicular emissions accurately due to inadequate representation of real-world driving. The focus of this paper is to understand the level of Indian Driving Cycle (IDC) in representing the real-world driving and to assess the impact of real-world driving on vehicular emissions. The study has revealed that IDC does not represent the real-world driving. Irrespective of road classes, about 30% of time is spent below 20 km/h and the speed too exceeds IDC's maximum limit of 42 km/h. Emissions are estimated for different driving patterns using International Vehicle Emission (IVE) model. Emission rates vary significantly from one class of road to another and the largest effect is on local streets.

***Key Words*:** Driving Cycle, Driving Characteristics, Speed Acceleration Frequency Distribution, Global Positioning System, International Vehicle Emission Model

## 1. Introduction

In India, vehicular emissions and energy consumption have been increasing considerably over last two decades especially in metropolitan cities. The National Environmental Engineering Research Institute (NEERI) has estimated that about 60 – 70% of total air pollution is caused by automobiles in all the major cities(1). In city centers road traffic accounts for as much as 90 – 95% of Carbon monoxide (CO), 60 – 70% of Oxides of nitrogen ($NO_x$) and Hydrocarbons (HC) and a major share of Suspended particulate matter (SPM)(2). According to studies about 20% of poorly maintained vehicles contribute about 60% of vehicular pollution in India(3). One study estimated that the pollution load increased from 0.15 million tons in 1947 to 10.3 million tons in 1997 from the transport sector alone. CO claimed the largest share (43%) in the total, followed by $NO_x$ (30%), HC (20%), SPM (5%), and $SO_2$ (2%)(4).

At present, fuel consumption and emissions are estimated based on average speed models such as LEAP (Long-range Energy Alternative Planning), VAPIS (Vehicle Air Pollution Information System) and spreadsheet model(5)–(7). Figure 1 shows the schematic diagram of general practice in estimating fuel consumption and emissions. As a first step fuel consumption and emission rates for different types of vehicles/technologies are estimated based on the average value of repeated experiments in a laboratory on a dynamometer by simulating the vehicles under standardized driving cycle (IDC). In the second step transportation data such as link speed and Vehicle Kilometers Traveled (VKT) are estimated. The total emission and fuel consumption are calculated by multiplying the results of these two steps.

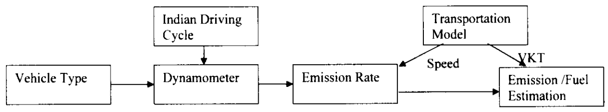


Fig. 1 Current emission estimation process

### 1.1 Driving cycles

Driving cycle is a sequence of vehicle operating conditions (idle, acceleration, steady state and deceleration) developed to represent typical pattern in an urban area. In India, driving cycle was developed by Gandhi et al. in early 80's to quantify fuel consumption based on a field study in Delhi(8). Later in 1985 ARAI (Automotive Research Association of India) collected extensive data in other cities (Mumbai, Chennai, Bangalore and

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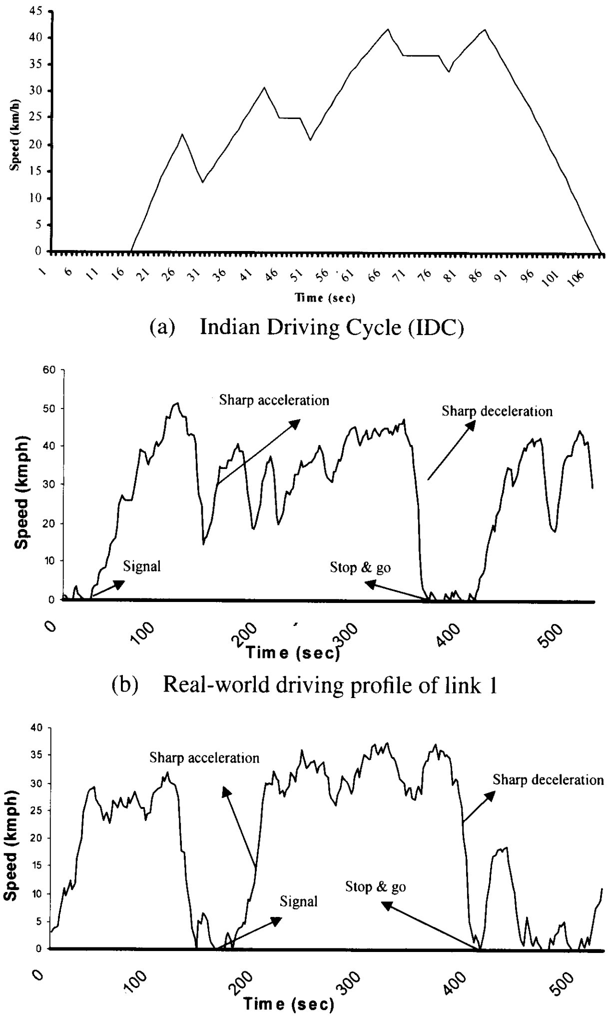


(a) Indian Driving Cycle (IDC)

(b) Real-world driving profile of link 1

(c) Real-world driving profile of link 2

Fig. 2 Comparison of driving cycles

Pune) to develop standardized/legislative IDC[9]. It is for about 108 seconds with average speed of 21.9 km/h and the maximum acceleration and deceleration are 0.65 $m/s^2$ and 0.63 $m/s^2$ respectively. From the year 2000, India has adopted modified Indian Driving Cycle for cars (same as ECE-15 +EUDC except maximum speed reduced to 90 km/h). These driving cycles were developed to test the compliance of Indian vehicles to Indian emission standards and to quantify fuel economy. It has different operating conditions with fixed time interval. Base emission rates for most of the in-use vehicles are estimated using IDC. Therefore, this study considers IDC shown in Fig. 2 (a) for further analysis.

As part of this research, a real-world driving profile in one of the Indian cities was observed while driving a Global Positioning System (GPS) instrumented vehicle. The cycle is shown in Fig. 2 (b) and (c). Comparing the IDC and real-world driving profile in Fig. 2, it can be noticed that IDC considerably differ from real-world driving. Real-world driving has frequent speed fluctuations and sharp acceleration and deceleration. These aspects are not satisfactorily represented in IDC. According to Guensler, sharp acceleration could increase emission rates by increasing the air to fuel ratio[10].

In Fig. 2 (b) and (c), the real-world driving for two links show completely different profiles though the vehicle and driver is the same for both the links. It shows a completely different profile. This might be due to a number of factors such as variation in road characteristics, traffic characteristics and roadway environment. A recent study has found that the average speed and acceleration are similar across a region, though frequency, duration and intensity of operating conditions were quite different[11]. In light of above discussion, the objective of this paper is two folds (i) to examine the ability of the IDC to represent the real-world driving pattern and (ii) to assess the influence of real-world driving on vehicular emission.

## 2. Literature Review

Previous studies have considered different variables in characterizing and developing driving cycles. Kent et al. analyzed driving cycle using average speed, root mean square acceleration and percentage of idle time[12], since it has significant influence on emissions. Kuhler and Karstens included a few more variables such as average acceleration, deceleration, mean length of a driving period from start to stop, average number of acceleration-deceleration changes within one driving period and proportion of different operating modes (idle, acceleration, cruising and deceleration) to characterize the driving cycle[13]. Later Watson established that positive kinetic energy (PKE) is one of the important factors which explain the variance in fuel consumption and emissions[14],[15]. Lyons et al. developed a technique to develop a driving cycle based on "Knight's Tour" by understanding the dynamics of urban driving[16]. Matzoros and Vliet added creeping mode to distinguish short acceleration and deceleration in the proportion of time spent in different operating modes[17].

## 3. Methodology

The real-world driving profile was captured through field study on different types of roads during peak periods. During the survey, speed data were collected second-by second. Study roads were selected broadly based on the IRC (Indian Road Congress) classification- arterial, sub-arterial, collector and local streets. Driving characteristics have been analyzed for each class of road.

Apart from driving characteristics, SAFD (Speed Acceleration Frequency Distribution) is constructed and analyzed for each driving pattern. It is commonly known as 'Watson plot'. Watson plot is a well known technique to compare different driving patterns. This technique was developed by Watson in 1976. It is a three dimensional plot of speed, acceleration and frequency: (i) divide the speed and acceleration at equal intervals (ii) calculate the joint frequency of these two factors[12],[14].

Following driving characteristics were estimated and analyzed for each driving pattern

- Average speed (km/h) – average speed of an entire trip
- Average running speed (km/h) – average speed of an entire trip excluding idle time
- Maximum speed (km/h) – maximum speed of an entire trip
- Average acceleration ($m/s^2$) – average acceleration of an entire trip
- Average deceleration ($m/s^2$) – average deceleration of an entire trip
- Maximum acceleration ($m/s^2$) – maximum acceleration of an entire trip
- Maximum Deceleration ($m/s^2$) – maximum deceleration of an entire trip
- Percentage of time spent in different operating modes
    - Idle – Speed equals zero.
    - Acceleration – Speed greater than 5 km/h and acceleration greater than 0.1 $m/s^2$.
    - Deceleration – Same as acceleration except that acceleration should be negative
    - Cruising – Speed greater than 5 km/h and acceleration should be greater than 0.1 $m/s^2$.
    - Creeping – Speed less than 5 km/h and acceleration and deceleration should be less than 0.1 $m/s^2$.

Source: Refs. (12) – (14) and (17).

There are number of studies relating driving characteristics and vehicular emissions using on-board measurement and remote sensing techniques. Conducting on-board measurement would be expensive and difficult to collect large number of vehicle samples. Further, technology is not available in developing countries like India. In the case of remote sensing techniques, it can be used only at a particular location and can capture instantaneous emissions alone. In this paper emissions are estimated for different driving patterns using International Vehicle Emission (IVE) Model.

IVE model was jointly developed by International Sustainable Systems Research Center and the University of California at Riverside. This model can calculate vehicular emissions at macro, meso and micro scale level. The general inputs to the model are fleet characteristics, vehicle activity and emission factor based on local conditions. IVE model estimates emission rates using Eq. (1) by adjusting for different correction factors.

To capture the driving behavior more accurately it uses Vehicle Specific Power (VSP) and enginestress. VSP estimated using three important factors - speed, acceleration, and grade[18]. These factors significantly influence emissions. Recent literature such as Refs. (19) and (20) were testimony to hypothesis.

$$Q[t] = B[t] * K(\mathrm{Base})[t] * K(\mathrm{Tmp})[t] * K(\mathrm{Hmd})[t] * K(\mathrm{IM})[t] * K(\mathrm{Fuel})[t]] * K(\mathrm{Alt})[t]] * K(\mathrm{Cntry})[t] * K(\mathrm{d})[t] \quad (1)$$

Where,

$Q[t]$: Adjusted emission rate for each technology
$B[t]$: Base emission rate in for each technology
$K(\mathrm{Base})[t]$: Adjustment to the Base Emission Rate
$K(\mathrm{Tmp})[t]$: Temperature Correction Factor
$K(\mathrm{Hmd})[t]$: Humidity Correction Factor
$K(\mathrm{IM})[t]$: Inspection/Maintenance Correction Factor
$K(\mathrm{Fuel})[t]$: Fuel Quality Correction Factor
$K(\mathrm{Alt})[t]$: Altitude Correction Factor
$K(\mathrm{Cntry})[t]$: Country Correction Factor
$K(\mathrm{d})[t]$: Driving or Soak Style Correction Factor (Also accounts for other load effects from air conditioning usage and road grade)

$$VSP = v[1.1a + 9.81(\mathrm{atan}(\sin(\mathrm{grade}))) + 0.132] + 0.000\,302\,v^3 \quad (2)$$

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

Where

$VSP$: Vehicle Specific Power
$v$: Velocity(m/s)
$a$: acceleration($m/s^2$)
$h$: altitude(m)

$$Enginestress(unitless) = RPMIndex + (0.08\ \mathrm{ton/kW}) * PreaveragePower \quad (3)$$

$$PreaveragePower = Average(VSP_{t=-5\ \mathrm{sec\ to}\ -25\ \mathrm{sec}})\ (\mathrm{kW/ton})$$

$$RPMIndex = velocity_{t=0}/SpeedDivider(unitless)$$

$$MinimumRPM\ Index = 0.9$$

### 3.1 Chennai city characteristics

Chennai is the capital city of Tamil Nadu and the fourth largest metropolis in India. It is situated on a 22 km stretch of the Coramandel coast. Chennai City is trisected by the waterways of Rivers' Cooum, Adyar and the Buckingham Canal. The city has a radial and ring pattern of road network. Household survey conducted by Central Institute of Road Transport in 1992 in 16 major cities including Chennai reveled that work and education trips constituted 40.7% and 41.57% respectively, while shopping and recreational activities accounted to balanced trips[21]. Chennai city depends on rail and road network for intra-city commuting. It has many arterial streets connecting the Central Business District (C.B.D) with outlying residential and industrial suburbs of the city. On an average trip rate in Chennai was 1.28 trips per day per person and the

Table 1 City characteristics

| | |
|---|---|
| City Population (2001) | 4.22 million |
| Area | 174 sq. km |
| Population density | 24,231 persons per sq. km |
| Number of registered vehicles | 1.5 million |
| Modal split[1] | 43% public transport |
| Annual fuel consumption (2001)[2] | Diesel – 298 TMT<br>Petrol – 152 TMT |
| Speed limit | Cars and 2-wheelers – 40 km/hr<br>3-whs and Buses – 25 km/hr |
| Road length[3] | 4179 |
| Number of motor vehicle accidents (2001) | 5280 |

[1] Ref.(34)

[2] Ref.(35)

[3] Ref.(36)

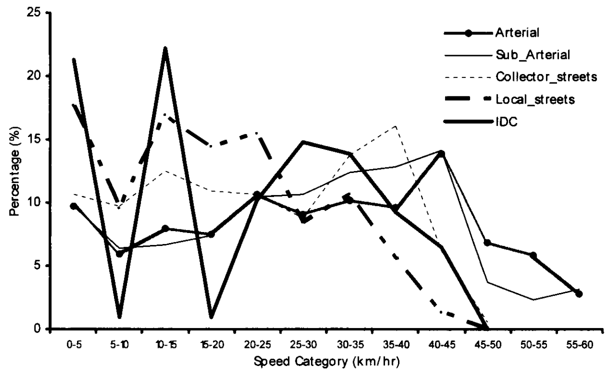



Fig. 3 Vehicle speed distributions

trip length was about 13 km(22). Chennai traffic was heterogeneous in nature, consisted about 20 different modes ranging from bullock carts to 21st century model car vehicles without any dedicated right of way. Average speed on important corridors during peak hours as low as 10 km/h. Table 1 shows basic profile of the city.

### 3.2 Data collection

A motor vehicle equipped with GPS was driven along study corridors at approximately average speed of the respective stream of traffic flow. Positional information and trajectory of the vehicle is recorded second-by second. Since the test vehicle traveled at the representative speed of traffic, actual traffic profile is captured. A second person in the vehicle noted down the starting and ending time of each trip to match the GPS time. The same person also noted down road names, odometer readings and duration, location and causes for individual delays. The vehicle came to a halt due to fixed and varying delays. Fixed delays are caused due to bridges, constricted carriageway or signals. Delay caused due to traffic congestion and on-street parking is termed as varying delay. Data were collected in the month of September 2004. Survey was conducted during the weekdays and it was ensured that there were no special occasions such as major processions or any abnormal activities in study corridor.

At the end of each trip data were downloaded to the computer in xml format and then converted to spreadsheet for further analysis. The qualities of the collected data were checked for errors and inaccuracies both visually and temporally. Driving patterns were constructed for different classes of road. Accuracy of the GPS readings were ranging from 5 m to 25 m. GPS data was overlaid on GIS Chennai map prepared using Arc map software. Both GIS map and GPS readings were converted to same coordinate system, and then spatial analysis method was applied to remove spatial errors of the GPS readings. Secondary data such as traffic volume, road length, number of lanes in each link, locations of on-street parking and detailed GIS map were collected from concern organizations.

## 4. Analysis of Driving Characteristics

Comparison of different driving characteristics with corresponding road and traffic characteristics throw more insight into various dimensions of real-world driving. Figure 3 shows vehicle speed distribution and the time spent in different speed ranges. Average speed was different across different types of road, though the difference was not substantially high due to high volume of traffic. Time spent in different speed also varies considerably. Irrespective of road types, about 30% of time was spent below 20 km/h and speed exceeded IDC's maximum speed of 42 km/h. In arterial and sub-arterial, more than 20% of time was spent at speed greater than 40 km/h. About 50% of time was spent at speed below 25 km/h in the case of collector streets and local streets. If it is assumed that 40 to 50 km/h is the free flow speed, then it occurs only at certain sections of the corridor. A recent study using on-board measurement established that emissions were low in speed ranges of 60 – 90 km/h. However, if speed falls outside these limits, emission increases considerably(23). In Chennai, vehicles spent nearly 90% of time below this speed range. This could be a reason for significant increase in vehicular emissions.

From Fig. 4 it was noticed that average running speed (excluding idle time) varies with different classes of roads. This was mainly due to variation in number of lanes and traffic characteristics along corridors. However, the IDC does not take these factors into consideration. Average acceleration and deceleration does not show any correlation among different classes of roads. Nevertheless, the variation within a single trip was substantial. This was due to unstable or forced traffic flow. Kelly and Groblicki have established that at sharp accelerations, CO and HC emissions were 2 500 times 40 times higher than normal

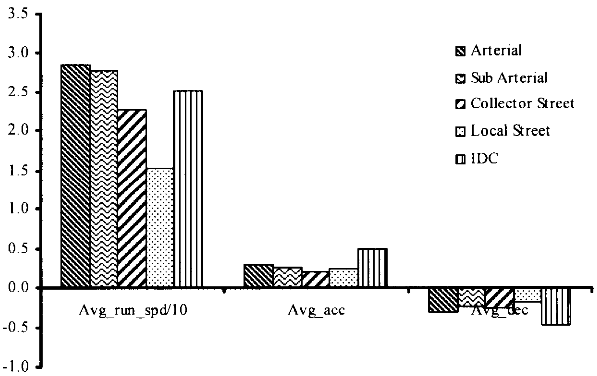



Fig. 4 Comparison of average running speed, acceleration and deceleration

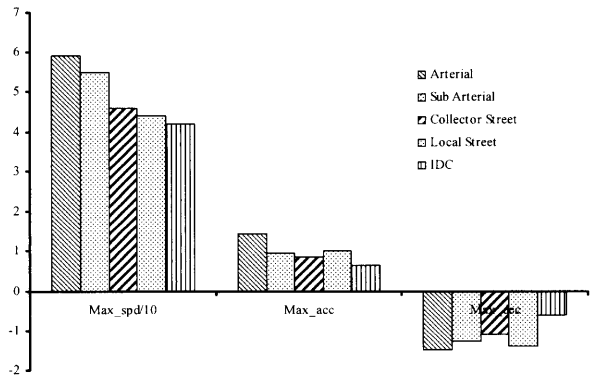



Fig. 5 Comparison of maximum speed, acceleration and deceleration

operation respectively[19]. In another study Bachman established that a single sharp acceleration can produce as much emission as an entire trip[24]. Congested traffic conditions increase emissions by 10 folds compared to free flow conditions[25]. On the contrary, the IDC does not take cognizant of these parameters.

As mentioned earlier, maximum speed in different types of roads has exceeded the maximum speed under IDC's. This indicates certain sections of the corridor have wider road widths and free flow conditions. Maximum accelerations and decelerations were 2 to 4 times higher than that by IDC. This explains the aggressiveness of the driving patterns. It occurs especially, when vehicles move on appearance of green light. This could increase emission and fuel consumption considerably. A recent research found that aggressive driving could increase fuel consumption up to 40% and emissions up to 8 times[26]. Rakha et al. have shown that acceleration at higher speed increases emission rates per unit of time[27]. Especially, latest vehicular technologies are much more sensitive than the older technologies[15].

In Fig. 6, it was observed that all types of roads have acceleration and deceleration greater than 30%. This indicates frequent variation in speeds of all classes of roads. Average speed was lesser on local streets. How-

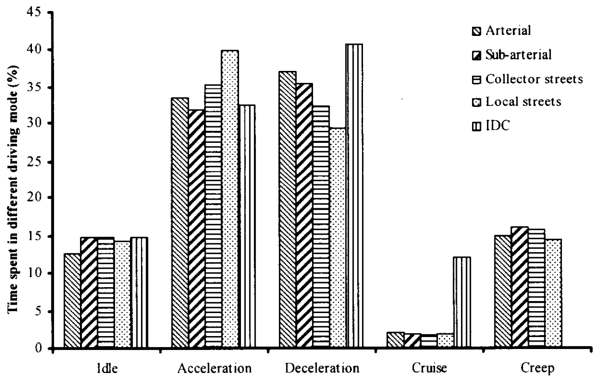


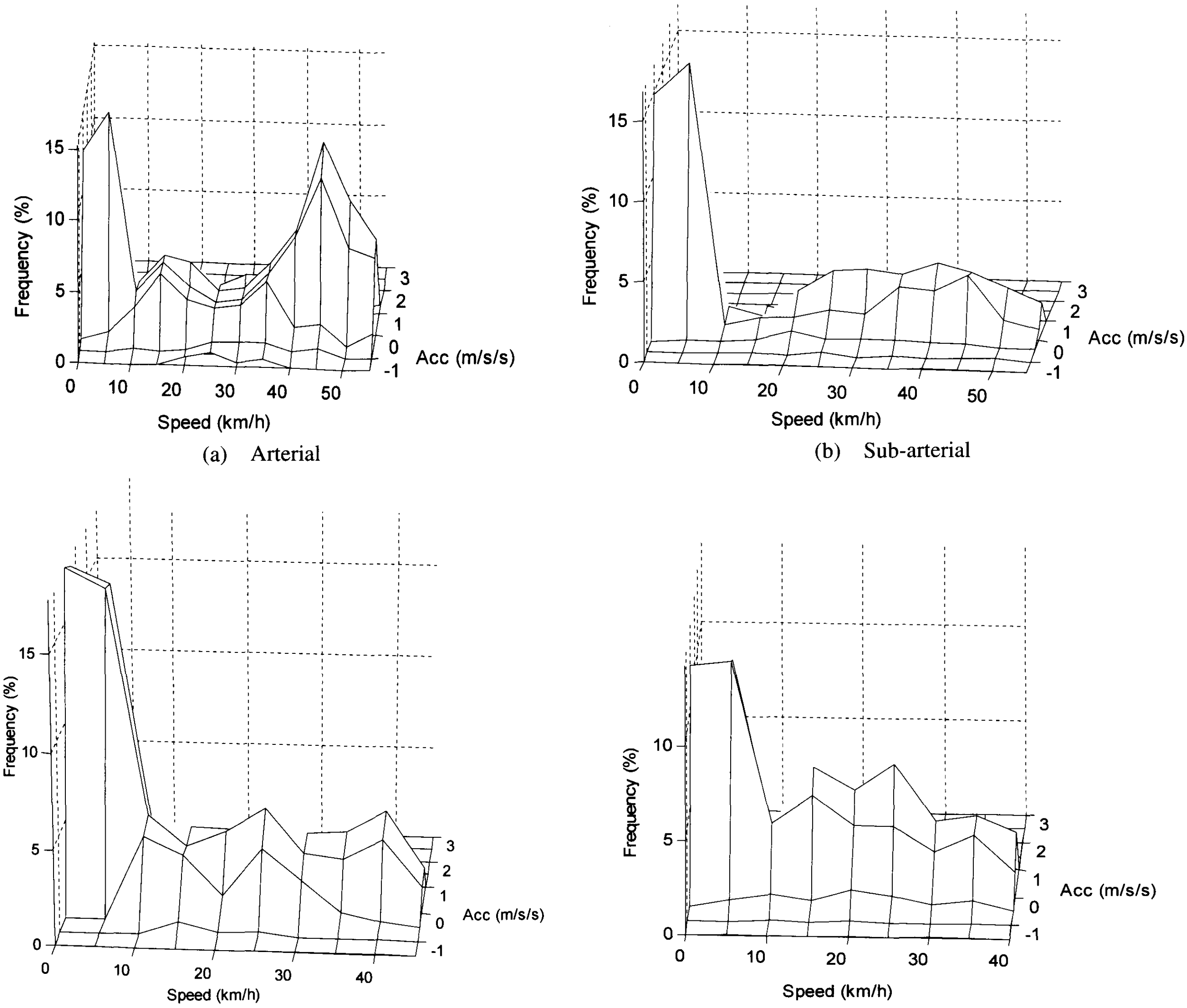

Fig. 6 Comparison of different operating conditions

ever, higher percentage of time spent in acceleration mode could be attributed to lesser number of fixed delays due to traffic lights. On the contrary, in both arterial and sub-arterial, every intersection was controlled by a traffic light. This brings about 35% of time in deceleration mode. Irrespective of road types, about 15% of time was spent in forced flow condition. This explains the frequent variations in speed. This occurs when vehicles approach traffic lights or when the flow was a forced one. Such a situation could cause significant increase in emissions. However, IDC does not capture such situations.

In this study, vehicle moving under free flow condition was less than 2% of the total time, contrary to the position under IDC, wherein free flow condition account to 12%. Idling operations also vary based on the class of road, though subtly. Above inferences clearly indicate that driving behaviour changes with road and traffic characteristics.

## 5. Speed-Acceleration Frequency Distribution

Figure 7 shows SAFD plot for different classes of roads. Speed axis ranging from 0 – 50 km/h with 10 km/h interval and acceleration axis was divided at 1 m/s$^2$ ranging from −2 to 3 m/s$^2$. Frequency axis is in terms of time spent in different speed-acceleration ranges. It was observed that nearly 15% of time was spent at 0 – 10 km/h speed range. In arterial, there were two peaks. One was at 0 – 5 km/h and it shows the existence of creeping mode and the second peak was at 40 – 50 km/h speed which could be attributed to free flow traffic conditions and wider roads. Sub-arterial was also similar to arterial except there was no dominant second peak. However it was uniformly spread over the speed range of 20 – 50 km/h. In case of collector streets, it has higher share of idle and creep than other classes of road. This could be due to the fact that during peak period green phase was lesser than that required at many intersections. This causes creeping. On the other hand on local streets lesser time was spent in idle and creep mode, though it reaches maximum speed of 40 km/h only. This was due to high share of slow moving traffic and




(a) Arterial (b) Sub-arterial (c) Collector street (d) Local street

Fig. 7 Speed acceleration frequency distribution for different classes of road

congestion.

## 6. Emission Estimation

To distinguish the influence of various driving patterns on vehicular emissions, emission was estimated using IVE model. Figure 8 compares different pollutants emission rate estimated using IVE model for different driving patterns. It can be observed that emission rates vary significantly from one class of road to another and the largest effect was on local streets. This was mainly due to local streets spending higher percentage of time in acceleration mode with low average speed. Both arterial and sub-arterial roads have almost similar emission rate except $NO_x$ which was higher in arterial. This could be attributed to sharp acceleration rate in arterial streets. $CO_2$ emission indicates lower emission in arterial street and higher emission in local streets. Though the fuel consumption was not estimated in this paper, $CO_2$ was directly related to amount of fuel consumed. This indicates that higher fuel consumption in local streets and lowers in arterial.

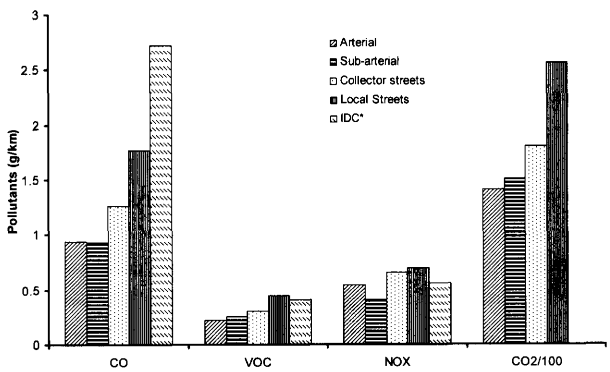



Fig. 8 Emission rate comparisons
*It includes start and running emission. $CO_2$ emission rate is not estimated in the case IDC

Figure 8 also shows emission rate for CO, HC and $NO_x$ calculated using IDC. In current practice emission rates are same irrespective of any driving patterns. Emission estimated using IDC includes start and running emission, whereas the emissions calculated using IVE model are only with running emissions. This has established that current emission models underestimates emission.

## 7. Discussions

Comparisons between the real-world driving patterns and IDC have been made in Chennai city. It has revealed that IDC does not represent the real-world driving. The analysis also gave a comprehensive view of the driving pattern in Chennai city. It has established that majority of the time vehicles spent at an average speed below 25 km/h. Aggressive driving is common in Chennai city. Further, it has confirmed that current practice underestimates the emission rates. Decision makers are carried away by current practice and hence the policies based on these estimates do not have any effect in emission reduction.

There are many reasons for underestimation. Some of them are as follows:

- Current emission models uses standardized driving cycle (IDC), which neglects the speed and acceleration greater than 42 km/h and 0.65 m/s$^2$ respectively.
- Current models assume that lower the vehicle speed higher is the emission. This study has established that emission increase at higher speeds. Recently, researchers have also found that higher speeds can also increase or decrease emission if conditions are not steady i.e., if there is any change in acceleration and deceleration which can happen at higher speed(28).
- Base emission rates are estimated based on the obsolete technology and small samples were used. Further, it relates emission rates based on single variables "average speed", whereas recent studies have shown that emission rates are more sensitive to acceleration than the average speed(29),(30).
- IDC assumes that all vehicle activities are the same irrespective of any variations in traffic and driving characteristics. This poorly represents the real-world driving patterns.
- IDC was developed under ordinary road conditions assuming that the grade is zero. Recent study found that grade influences emission significantly. CO and $NO_x$ emission were twice as high in uphill (approx. 4% grade)(31).
- IDC does not differentiate between different classes of roads, where speed and acceleration frequency are different due to street design, traffic lights, congestion level that could influence emission rates.
- New and well tuned vehicles are used for emission rate estimations.
- Current practice balances the operating conditions (acceleration, deceleration, idle, creeping and cruise) hence it cannot be used to analyze improvements due to traffic management schemes such as roundabouts, signal co-ordination, road widening etc.
- India has recently adopted modified Indian Driving Cycle for cars, though it considers speed and acceleration greater than 42 km/h and 0.65 m/s$^2$ respectively. However, this also doesn't replicate the real-world driving, which is a serious concern.

## 8. Conclusions

It is clear from this study that there is a need to develop driving cycles to estimate emissions and fuel consumption more accurately. The new driving cycle should represent real-world driving characteristics such as higher speed and acceleration than the current driving cycles. Further, it should distinguish between different classes of road and locations rather than aggregating to a single driving cycle. Studies have shown that traffic density, number of intersections, speed limit, modal mix, street functions and type of landuse influences the driving patterns, which should also be considered when developing a new driving cycle(32),(33).

Countries like Australia, UK, Germany and France have developed driving cycles to estimate emission and fuel consumption apart from legislative driving cycles, which include extreme driving conditions (higher speed and accelerations). India should also consider similar approach.

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