Analysis and Estimation of Vehicular Fleet Emissions in the Islamabad City

By

Izhar Hussain Shah

(2013-NUST-MSPhD-EnvE-18)

A thesis submitted in partial fulfilment of the requirements for the degree of

Master of Science

In

Environmental Engineering

Institute of Environmental Sciences and Engineering (IESE)
School of Civil and Environmental Engineering (SCEE)
National University of Sciences and Technology (NUST)
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It is certified that the contents and forms of the thesis entitled

Analysis and Estimation of Vehicular Fleet Emissions in the Islamabad City

Submitted by

Izhar Hussain Shah

Has been found satisfactory for the requirements of the degree of
Master of Science in Environmental Engineering

Supervisor: ____________________
Dr. M. Zeeshan Ali Khan
Assistant Professor
IESE, SCEE, NUST

Member: ____________________
Dr. Ishtiaq A. Qazi
Professor
IESE, SCEE, NUST

Member: ____________________
Dr. Fahim Khokhar
Assistant Professor
IESE, SCEE, NUST

External Member: ____________
Dr. Thongchai
Lecturer
Walailak University, Thailand.

Dedicated to……

My beloved parents & respected teachers

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“Izhar Hussain Shah”

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LIST OF ABBREVIATIONS

BC	Black Carbon
BEF	Base Emission Factor
CDA	Capital Development Authority
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPERT	Computer Programme to Calculate Emissions from Road Transport
EF	Emission Factor
EI	Emission Inventory
FTP	Federal Test Procedure
GHGs	Greenhouse Gases
GPS	Global Positioning System
HC	Hydrocarbons
HDIP	Hydrocarbon Development Institute of Pakistan
I/M	Inspection and Maintenance
ICTA	Islamabad Capital Territory Administration
ISSRC	International Sustainable Systems Research Center
IVE	International Vehicle Emissions (Model)
LDV	Light Duty Vehicles
MOVES	Motor Vehicle Emission Simulator
MPFI	Multi-Point Fuel Injection

N_2O	Nitrous Oxide
NH_3	Ammonia
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
OTAQ	Office Of Transportation and Air Quality
PEMS	Portable Emission Monitoring System
PM	Particulate Matter
SO_2	Sulfur Dioxide
SOx	Sulphur Oxides
US-EPA	United States Environmental Protection Agency
VKT	Vehicle Kilometers Traveled
VOCs	Volatile Organic Compounds
VSP	Vehicle Specific Power

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ABSTRACT

Air quality management and planning requires regular monitoring and accurate local emission estimates that are calculated on the basis of local conditions and controlling factors. To assess the contribution of light duty vehicles (including passenger cars, taxis, vans and motorcycles), to Islamabad's outdoor air quality, daily emissions were calculated with the help of IVE emission model. Results revealed a higher average age for these vehicles with taxis having an average age of 20.4 years and a significant share in overall pollutant emissions. Lower number of Euro compliant vehicles was also found during this study. Pre-Euro vehicles were found to be greatly responsible for higher emissions. Higher number of gasoline fueled vehicles was observed for each vehicle type (>80 per cent). Low engine stress modes (lower speeds with frequent decelerations) were observed for all vehicles especially on arterials and residential roads. This can be attributed to the rapid increase in vehicle population, ongoing construction of a mass transit bus project in the city, diversions and partially blocked roads for security purposes, and higher number of traffic signals. Highest overall emissions (59 per cent) were observed on arterials, followed by residential roads (24 per cent) and highways (17 per cent) with higher emissions observed during morning (8-10 am) and evening (4-6 pm) hours. Consequently, composite emissions factors were calculated and used to estimate annual emission inventory for Islamabad. Results showed that annually, 1093 kt of CO_2, 147 kt of CO, 18.5 kt of VOCs and 11 kt of NOx were emitted by light duty vehicles during the year 2014.

Chapter 1

INTRODUCTION

1.1 Background

Atmospheric pollution is harmful to both human health and environment with urban air pollution having an economic impact as well (Sonawane *et al.,* 2012; Franco *et al.,* 2013). Considering its impact on human health, 3.7 million premature deaths were reported to be related to outdoor air pollution worldwide during the year 2012 (WHO, 2014). Road traffic emissions are known to be a major contributor to air pollution (Kanabkaew *et al.,* 2013). Likewise, many source apportionment studies have reported road transportation to be largely responsible for urban particulate air pollution (Maykut *et al.,* 2003; Querol *et al.,* 2007). This problem is observed in many cities and urban centers due to growing vehicle population and is likely to result in more emissions in future as well (Franco *et al.,* 2013).

Vehicular emissions have several environmental consequences including formation of tropospheric ozone (Jiang and Fast, 2004; Matthes *et al.,* 2005; Gao, 2007; Nagpure *et al.,* 2011), airborne suspended particulate matter (Shah and Shaheen, 2007), acid rain, greenhouse effect, production of ozone precursor pollutants etc. (Yu *et al.,* 2009).

Though, developed countries have established improved vehicle emission control technologies coupled with stringent emission standards, but developing countries are far behind. Weak understanding and quantification of vehicular emissions (resulting from lack of resources) along with less stringent environmental standards in developing countries like Pakistan etc., aggravates this problem and that too with a rapidly increasing number of vehicles.

1.2 Understanding Emissions from Vehicles

Vehicular emissions consist of several toxic air pollutants and climate forcing pollutants which include Greenhouse gases (GHGs), black carbon (BC) and ozone precursors (Shrestha *et al.,* 2013). GHGs contributing towards global warming and listed in 1998's Kyoto Protocol include, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Lee *et al.,* 2013). These emissions are considered to be an important contributor to NOx, particulate matter (PM), sulphur oxides (SOx) and CO (Hyder *et al.*, 2006). Vehicles are said to be responsible for around 90 per cent of CO_2 emissions generated from the transportation sector (Nakata, 2003). In United States alone, around 82 per cent carbon monoxide (CO), 56 per cent nitrogen dioxide (NO_2), 45 per cent volatile organic compounds (VOCs), 12 per cent lead (Pb), and 5 per cent sulfur dioxide (SO_2) emissions were attributed to the transportation sector. While in China, around 85 per cent CO, 71 per cent nitrogen oxides (NOx), and 45 per cent VOCs emissions were attributed to vehicles (Zhang *et al.*, 2013).

1.3 The Case of Pakistan & Its Capital

South Asian countries like Pakistan have been undergoing rise in urban population with more growth focused in major cities (IGES, 2005). In Pakistan, therefore, this rise in urban population has resulted in bringing more vehicles on the roads. This rise in vehicle ownership has been attributed particularly to absence of alternate modes of transportation in the country. Previously estimated vehicle growth rate in Pakistan has been reported to be around 10 per cent per year with large part observed in urban areas (Hyder *et al.*, 2006). More recent records show that from the year 2001 to 2010, national vehicle population increased from 4.78 million to 7.85 million with an average annual growth rate of 5.78 per cent during that period (PBS, 2011). Fast growth in traffic volumes has resulted in considerable increase in emissions of air pollutants in Pakistan (Majid *et al.*, 2012).

Higher pollution levels resulting from road traffic have been observed in Pakistani urban areas (Mehboob and Makshoof, 2008). While the world is moving towards more cleaner vehicles, it is reported that an average vehicle in Pakistan will release 20 times more hydrocarbons (HC), 25 times more CO and 3.5 times more nitrogen oxides (NOx) in grams per kilometer than an average vehicle in the United States (Pakistan Strategic, 2006; Khan and Yasmin, 2014). Reasons for such a grim condition may include weaker air quality management planning along with higher vehicle technology mix and older vehicles causing increased air emissions. Other factors include poor fuel utilization, low average speed mainly due to congestion, and reduced overall performance of our transportation systems as reported earlier by Shabbir and Ahmad (2010). These factors indicate the amount of work Pakistan has to do in order to overcome impending environmental challenges emanating from the transportation sector. Unfortunately, very little work has been done to understand the environmental implications of our road transport and the speed of improving the existing situation is very slow.

Pakistan adopted to Euro 2 equivalent emission Standards and introduced a set of emission limits for all new and in use vehicles. These were also termed as Pak-II tier replacing vehicle exhaust and noise standards of 1993. These Pak-II standards were subdivided into light and heavy diesel vehicles and gasoline fueled vehicles which include passenger cars, light commercial vehicles, three wheelers (rickshaws) and motorcycles. Incorporating emission limits for CO, HC, NOx and PM, these standards for PM, however, did not define if they were applicable to PM_{10} (particles with aerodynamic diameter of 10 micrometers or less) or $PM_{2.5}$ (particles with aerodynamic diameter of 2.5 micrometers or less) emissions. The schedule for implementation was over two deadlines. First was the immediate implementation from July 1st, 2009 for gasoline vehicles while second was from July 1st, 2012 for diesel vehicles (Sánchez-Triana *et al*, 2014).

1.3.1 The City of Islamabad

Islamabad is the capital city of Pakistan located in the Potohar Plateau in the north west of Pakistan with an elevation of 500 meters above sea level. Islamabad is located at latitude of 33.71° North and longitude of 73.1 ° East, and is bordered by Margalla hills on one side (North) and plains of an adjunct province (Punjab) on the other side. The city of Islamabad is spread over an area of 906 km^2 with a reported population exceeding one million (Qadir *et al.,* 2012; Ulfat *et al.*, 2012). Having the status of federal and administrative capital, Islamabad city has a national importance as well. This significance of Islamabad has always invited new dwellers into the city that has resulted in a constant expansion of urban population (Adeel, 2010).

One of the consequences of such a population increase is the massive rise in the transportation flux observed during the last decade (Shah and Shaheen, 2010). Easy availability of passenger vehicles on lease from commercial banks has also contributed towards the increasing vehicle population which in turn has increased the air pollution in the city (Faiz *et al.,* 2009). Figures for the last five years have also shown an average annual addition of 62,000 vehicles in the city’s overall fleet.

1.4 Relevance to National Needs

We, therefore, undertook this research work to understand the contribution of Light Duty Vehicles (LDVs) and public transport vehicles, which include passenger cars, taxis, vans and motorcycles, to urban air pollution in this city and to estimate the overall atmospheric emissions by these vehicles. These four vehicle types constitute a major share (~97 per cent) in the onroad vehicles in this city mainly due to no adequate public transport system and the fact that many out-of-city commuters visit Islamabad on their vehicles on daily basis. Once the vehicular emissions for Islamabad are estimated, mitigation of vehicular emissions can be planned for a cleaner environment. These mitigation measures include the use of improved engine technologies (e.g. Euro III, Euro IV, 3-way catalytic convertors etc.), provision of improved fuel quality (e.g. lower sulphur content, Compressed Natural Gas (CNG) etc.), and better transport planning in order to optimize emission reductions.

Emissions were estimated using the International Vehicle Emission (IVE) model. The IVE model can be used for the estimation of dynamic, rather than static, vehicle fleet emissions on the basis of driving pattern and technology distribution of a certain area with low-cost methods to collect local data (Lents *et al.*, 2004 a; CAI, 2014). Developed jointly by researchers at the International Sustainable Systems Research Center (ISSRC) and the University of California, Riverside with US-EPA's funding, IVE model's basic theory has been termed as credible by US-EPA (Davis et al., 2005; Liu et al., 2007) and has been mostly used for national and regional emission inventories (EI) (Shorshani *et al.*, 2015).

Scarcity of research in the proposed area together with the urgent need for the implementation of air quality improvement programs necessitates this work. This work will enable us to determine the baseline vehicular emissions in Islamabad city, and will also help in evaluating future mitigation/management plans and their effectiveness. Moreover, this study will also help to establish emission inventory (EI) for Islamabad which will purely be based on local conditions and driving patterns, and other cities of Pakistan can follow this work and establish their own EI in near future.

1.5 Main Study Objectives

This research work was designed around two major objectives i.e.

1. Analysis of the vehicular fleet in the Islamabad City.
2. Estimation of vehicular emissions from light duty vehicles in Islamabad.

Chapter 2

REVIEW OF LITERATURE

2.1 Introduction

Transportation is exacerbating the poor urban air quality with on-road vehicles being the major contributors to air pollution in developing countries in particular (Lents *et al.*, 2005; Guo *et al.*, 2007 a; Yu *et al.*, 2009; Zhang *et al.*, 2013). Having an impact on both on a local and global scale (Karlsson, 2004), vehicles are also responsible for contributing to hazardous air pollutant emissions (Zhang *et al.*, 2011). Source apportionment studies have frequently attributed a major share of urban pollution to road transportation (Maykut *et al.*, 2003; Querol *et al.*, 2007). For example, Whitlow *et al.* (2011) reported an ultrafine PM concentration varying linearly with traffic flow in the New York City. Similarly, Wang *et al.* (2008) and Li *et al.* (2012) have reported the significant impact of vehicular emissions on air pollution in the major Chinese cities while a similar trend is seen in Europe with fast increasing GHG emissions from transport sector (Pasaoglu *et al.*, 2012).

There are an estimated 800 million vehicles on the road today and without interventions, that number is set to grow to 2-3 billion by 2050 (WRI, 2014). With a rapid rise in vehicle population since last few decades, increased efforts to address its environmental implications have also been seen in many countries including USA and China (ADB, 2003; Hao *et al.*, 2007; Vijayaraghavan *et al.*, 2012). These efforts are observed with a focus on reducing the imminent adverse impact of these emissions on health, society, economy and environment (Lents *et al.*, 2005; Lents *et al.*, 2007 c; Yu *et al.*, 2009; Sonawane *et al.*, 2012). In spite of their significance, vehicular emissions are inadequately understood and quantified in developing countries (Guo *et al.*, 2007 a). Lack of required resources to quantify these emissions has been seen as an impediment for the assessment of existing situation in developing countries.

2.2 Quantifying Vehicular Emissions

Methods of measuring vehicular emissions include determination of vehicular emission profiles and effect of operational variables (driving conditions/patterns, climatological variations, fuel quality etc.) either under controlled laboratory conditions or real world conditions. Engine and chassis dynamometer test is undertaken in controlled conditions whereas real world condition tests include tunnel studies, remote sensing measurements, on-road and on-board measurements (Kuhns *et al.,* 2004). Another approach of predicting vehicular emissions is the use of prediction models especially developed by USA and Europe. These emission models use factors such as vehicle type, driving pattern, local climatological condition, Inspection and Maintenance (I/M) program, and emission standard, to calculate transportation emissions (Franco *et al.,* 2013; CARB, 2014; EEA, 2014; US-EPA, 2014). Previous research so far has focused on various areas including measurement technologies, prediction models, emission reduction strategies, emissions regulation and legislative actions etc. There are various studies and reviews by many researchers in areas concerning quantification of vehicular emissions providing details and clarifications on many specific and narrowed topics (Yu *et al.,* 2009).

Preparation of EI requires precisely calculated Emission Factors (EF) and such an exercise is, most of the time, highly dependent on resources. For example, direct measurement method such as the chassis dynamometer test in laboratories is simple but costly and only fewer vehicles can be tested (Kim Oanh *et al.,* 2010). Other direct measurement methods include Portable Emission Measurement System (PEMS) (US-EPA, 2005), remote sensing (Chan *et al.,* 2004), and on-road mobile laboratory (Zavala *et* *al.,* 2006). These methods can be adopted in complete real world conditions on a larger number of vehicles, yet they may warrant sufficient resources.

On the other hand, indirect measurement methods include modeling of vehicular emissions which can also examine large number of onroad vehicles in near real world conditions. Generally, emission modeling relies on lesser resources and has been employed in several studies, and for this reason, traffic EI is usually prepared following the emission modeling approach (Davis *et al.,* 2005; Kim Oanh *et al.,* 2012). In emission modeling, individual vehicle emission measurements are not required thus the costly direct emission measurement tests are averted (Franco *et al.,* 2013). Modeling can incorporate high number of default EFs for a larger number of vehicles having differing engine technologies, fuel types and exhaust emission control equipment that is usually observed in every vehicle fleet (Kim Oanh *et al.,* 2012). Base Emission Factors (BEFs) used in emission models such as MOBILE (US-EPA, 2015), California Air Resources Board's EMFAC, and IVE model are derived from real measurements and from chassis dynamometer tests conducted in the U.S. (Guo *et al.,* 2007 b).

For EI of vehicles conforming to European emission standards, as in Europe, Computer Programme to Calculate Emissions from Road Transport (COPERT) model is preferred (Goyal *et al.,* 2013; EC, 2014). These emission models can be and have been used in developing countries. However, faster vehicle deterioration, different driving conditions, vehicle technologies, and fuel types are likely to give dissimilar EFs than those observed in Europe and U.S. (Zhang *et al.,* 2008; Kim Oanh *et al.,* 2012). Moreover, most of these region specific models may produce inaccurate emission estimates for other regions (Wang *et al.,* 2008). This necessitates the use of modified emissions factors that are pertinent to local conditions.

Emissions models are mainly characterized as travel based or fuel based. The later type can use direct measurement methods to determine EFs per unit fuel consumed acquired from governmental records thus creating a fuel based emission inventory such as the COPERT model (EEA, 2000; Pokharel *et al.,* 2002). In travel based models, region specific EFs and travel statistics are combined to produce EI such as in MOBILE, EMFAC, and the IVE model. The research trend has been found as moving towards combining emissions models with transportation and simulation models for more accurate estimates (Yu *et al.,* 2009).

2.2.1 Importance of Quantifying Traffic Emissions

The continuous expansion in vehicle population coupled with deteriorating driving conditions (mainly due to congestion) have signified the use of traffic emissions and their projections in air quality management and climate change control strategies (Smit *et al.*, 2010). In policy making, measurement of EI and their projections play a very significant role in managing the overall air quality in a given area. Noland and Quddus (2006) have recommended the use of local factors and technology advancements (which represents real world conditions in an accurate way) in estimating EI. Smit *et al.* (2009) has pointed out the increase both in the complexity and broadness of emission models over time. This complexity, however, can be justified with an increase in vehicle population, and types of fuels, pollutants and emissions (e.g. start, running, evaporative) being considered in these emission models.

In the last two decades, important research efforts have been made worldwide to study the effect of policies to reduce pollutant emissions from onroad vehicles (Lumbreras *et al.,* 2008). For example, Seika *et al.* (1998) analyzed various traffic control plans and their varying emissions, Saelensminde (2004) provided a cost benefit analysis of non-motorized transport, Shrestha *et al.* (2005) worked on a cost effective transportation method for the reduction of NOx emissions, Hao *et al.* (2006) assessed several factors for reducing vehicle emissions, and Kim Oanh *et al.* (2012) and Shrestha *et al.* (2013)

analyzed benefits of improved technology implementation and its potential impact on global warming.

2.3 Factors Affecting Vehicular Emissions

Onroad vehicles can generate 300 times different emissions from each other even when operated on similar roads (GSSR, 2004). Although vehicular emission profiles are highly dependent on vehicle technology type, driving pattern, and local geography and climate along with types of fuel used, but among them, the most important is the vehicle technology distribution when analyzing onroad vehicular emissions (Ntziachristos and Samaras, 2000; Huang *et al.,* 2005). Vehicle technology type can be categorized by its engine size and air-fuel management technique, emission control method, type of fuel used, vehicle overall use and its age (Lents *et al.,* 2004 a). Vehicle age is also considered to be an important factor with old vehicles generating more emissions as compared to newer ones. It is reported in the literature that in developed countries, upto 70 per cent emissions come from only the 10 per cent most polluting vehicles (Pokharel *et al.,* 2002; Bishop *et al.*, 2003 a; Bishop *et al.*, 2003 b). While Guo *et al.* (2006) have attributed 60 per cent of emissions to 20 per cent of the vehicles that are older than 10 years. This also justifies the fact that deteriorating vehicle condition significantly increases pollutant emissions from vehicles as previously reported by Sawyer *et al.* (2000).

Another important factor is the driving pattern which is defined by a measured velocity profile of the local driving along with the number and times of starting the vehicle and distance traveled each day (Lents *et al.,* 2004 a; Yao *et al.,* 2007; Fu *et al.,* 2013). Vehicles operating in variety of conditions produce a significantly transitory pattern with higher loads (e.g. acceleration and high speeds) giving off considerable amount of emissions (Davis *et al.,* 2005; Franco *et al.,* 2013). Local conditions affecting vehicular emissions include factors such as fuel characteristics, ambient temperatures and humidity, road elevation and grade along with local travel factors such as its demand and cost, traffic conditions and preference for the public transportation vehicles (Tong *et al.,* 2000; Lents *et al.,* 2004 b; Hao *et al.,* 2011).

2.4 IVE Model & Its Considerations

The IVE model can be used for the estimation of dynamic vehicle fleet emissions on the basis of driving pattern and technology distribution. The IVE model considers various technologies and local conditions prevailing in many developing countries along with their driving patterns. This include factors having a significant effect on tailpipe emissions such as average Vehicle Kilometers Traveled (VKT), Vehicle Specific Power (VSP) developed by Jiménez (1999) and different engine stress modes (Guo *et al.,* 2007 a; Zhang *et al.,* 2009). VSP is defined as the power required by the engine to operate the vehicle at a given speed and acceleration divided by the mass of the vehicle (Jiménez, 1999; Kuhns *et al.,* 2004).

IVE model was designed keeping in view the needs of developing countries by providing a policy making tool (Lents *et al.,* 2004 a). IVE model is considered flexible with respect to its application in developing countries (Nicole *et al.,* 2005) and has been validated in several countries (Mishra and Goyal, 2014). Method for incorporating local fleet information in IVE model has been found low-cost with a facility of using data from other studies when local data is absent (CAI, 2014). Its application to some of the polluted cities has brought promising results (Kim Oanh *et al.,* 2012).

IVE model is a versatile and easy-to-operate standalone Java computer program which is able to project vehicular emissions for any location provided three types of input i.e. (i) vehicle engine technology and exhaust control distribution of a fleet including maintenance, (ii) local driving pattern recorded on different types of vehicles (including vehicle soak distributions), and (iii) local emission factors particular to those vehicles

(Wang *et al.,* 2008). All these factors are considered to have a considerable effect on the exhaust emissions from a hot-stabilized gasoline-run vehicle (Guo *et al.,* 2007 b).

Instead of using emission factors derived from average speed, as in MOBILE model, the IVE model is based on driving cycles developed from VSP bin distributions on a per-second level. IVE model consists of default emission factors for 1371 vehicle technology types. IVE model can be considered as the most accurate model for developing countries (Lents *et al.,* 2001; Liu *et al.,* 2007; Davis and Lents, 2010).

It (IVE model) is also termed as an international version of Motor Vehicle Emission Simulator (MOVES) which was developed by the Office of Transportation and Air Quality (OTAQ) as US-EPA's official model for estimating emissions from cars, trucks and motorcycles (CAI, 2014; US-EPA, 2015).

2.4.1 Emission Types Included

The three types of emissions considered by IVE model include (i) emissions of a stabilized operating engine (usually termed as hot or running emissions), (ii) exhaust emissions after a cold engine start (cold start emissions), and (iii) evaporative (mainly VOC) emissions (Kim Oanh *et al.,* 2012). Excessive emissions during the initial 200 seconds of an engine start, whose soak time is greater than 18 hours, are termed as cold-start emissions. The extra emissions during the initial 200 seconds of an engine start, of an already warm engine, are considered as warm-start emissions (Lents *et al.,* 2005; Lents *et al.,* 2007 a). Whereas the vapors escaping from the vehicle and the refueling emissions are termed as evaporative emissions (Collet *et al.,* 2012).

2.4.2 Emission Factors

Emission of pollutants relative to the activity producing them is given by experimental values termed as EF. These EFs can forecast the amount of a pollutant that will be released relative to the distance travelled, fuel consumed, or energy utilized for operation. IVE application includes the use of default emission factors together with collected local data. However, availability of locally measured emission factors is considered more appropriate and can be used to create adjusted emission factors in the IVE model.

EFs are affected by driving and ambient conditions, fuel characteristics, vehicle technology and emission control equipment (Franco *et al.*, 2013). Their accuracy is of utmost importance when estimating vehicular emissions for a given area (Zhang *et al.*, 2013). The default EFs in the IVE model are developed by incorporating data from a huge number of vehicles in the U.S. by testing them on Federal Test Procedure (FTP) driving cycles (Guo *et al.*, 2007 b). However, these default EFs can be modified in the IVE model, if locally developed EFs are available (Wang *et al.*, 2008).

2.4.3 Vehicle Specific Power

Unlike MOBILE and COPERT which use mean velocities (missing extreme emissions under high engine stress modes), IVE model uses VSP distribution to produce instantaneous emissions on a random driving cycle (Sawyer *et al.*, 2000; Wang *et al.*, 2008, Goyal *et al.*, 2013). Variations in vehicular emissions with respect to variations in driving pattern and speed are best predicted by VSP (Huan *et al.*, 2005; Lents *et al.*, 2007 a). VSP has been shown to be closely related to vehicular emissions than the acceleration and/or speed (Jiménez, 1999; Kuhns *et al.*, 2004; Wang *et al.*, 2008). VSP characterizes the driving behavior with respect to the study area and can account for nearly 65 per cent variance in vehicular emissions (GSSR, 2004; Guo *et al.*, 2007 b).

IVE model considers 60 VSP bins to account for different driving speeds and patterns. Different driving patterns produce different emissions and this variation is represented by 60 different bins of VSP (Lents *et al.,* 2005). Every point of the driving route is assigned to a bin amongst 60 VSP bins which are further divided in 3 engine stress modes of 20 bins each, with each driving bin generating different emission rates. Local driving pattern can be measured by using global positioning System (GPS) which can give second-by-second vehicle location (Latitude, Longitude, and Altitude) and its second-by-second velocity traces (Barth *et al.,* 1996; Liu *et al.,* 2007). The experiments in the U.S. comparing GPS measured velocity profiles with average traffic velocities have validated the use of GPS for the determination of local driving patterns (Davis *et al.,* 2005).

2.4.4 Vehicle Activity & Driving Patterns

Vehicle activity is also determined and subsequently used in IVE modeling, and includes determination of quantity and pattern of driving taking place in an area of interest together with the average number of vehicle start-ups. Vehicle driving patterns are obtained from the use of GPS devices fixed to subject vehicles followed by the determination engine power demand per unit vehicle mass to incorporate impact of driving pattern on exhaust emissions, this power factor (or VSP) is arranged over 60 respective VSP bins (Davis *et al.,* 2004). On the other hand, vehicle starts also contribute significantly towards total exhaust emissions and can be as high as 50 per cent of overall emissions in some cases. While in U.S., start-ups emissions contribute 10 to 30 per cent towards total emissions which underlines the importance of understanding vehicle starting patterns of an area for accurate emission projections (Lents *et al.,* 2004 b; Davis *et al.,* 2005). Cold start-ups are responsible for significant emissions from vehicle start and occur when an engine is completely cooled off (Schifter *et al.,* 2010).

2.5 Studies by IVE Model

Ever increasing number of onroad vehicles in developing countries with fastest rates of urbanization, have signified the importance to estimate and address environmental impacts arising from these emissions (Davis *et al.,* 2005; UN-Habitat, 2013). Several developing countries have opted for modified versions of U.S. or European based emission models and emission factors mainly due to lack of local data and resources to estimate vehicular emissions. These efforts are made on the premises that same vehicle technologies will produce same emissions without any regard to the area of manufacture or use. Although this approach gives a baseline of vehicular emissions, application of these emission models and EFs to an outside region without incorporating local factors can be highly problematic (Davis *et al.,* 2005).

With an availability of a comprehensive vehicle technology distribution, IVE model can be employed by other countries as IVE emission factors are established on thorough vehicle technology classifications with an advantage of modifying them as per local conditions (Liu *et al.,* 2007). Performed in a systematic manner, IVE model first requires determining local vehicle technology distribution by using both the traffic video recordings and questionnaire surveys to calculate fractions of onroad vehicle types and technology distribution of vehicles (e.g. engine technologies, model years, odometer readings, emission control devices, and fuel types) respectively. IVE model has been applied for EI in several cities in developing countries including Mexico City (Mexico), Pune (India), Sao Paulo (Brazil), Beijing and Shanghai (China), Kathmandu (Nepal), and Hanoi (Vietnam). These studies have predicted pollutants most relevant to urban air quality including CO_2, CO, SOx, NOx, VOCs, PM, lead, CH_4 etc. along with toxic pollutants such as formaldehydes, acetaldehydes, benzene, ammonia and 1,3 butadiene. Some of the major studies, using IVE model, performed in various parts of the world are summarized in Table 2.1.

Table 2.1: Summary of studies conducted worldwide by using IVE model

Reference	**Study**	**Findings**
Mishra *et al.,* **2014**	Used dynamic emission factors for emission estimates.	Estimations consistent with monitored concentrations of CO, NOx and PM_{10}
Shrestha *et al.,* **2013**	Emission reductions under alternate vehicle scenarios.	44% reduction for toxic pollutants and 31% reduction for climate forcers by upgrading vehicle fleet.
Zhang *et al.,* **2013**	Analyzed emission reduction policies from 2009-2030.	Highest reduction under 'increased fuel economy' as compared to 'alternative fuel scenario'.
Kim *et al.,* **2012**	Estimated emissions from 2 million motorcycles & benefits of Euro 3 upgrade.	Euro 3 Implementation reduced total emissions up to 94% & climate forcers up to 53%.
Nagpure *et al.,* **2011**	Investigated the impact of altitude on ozone precursors emissions from LDVs.	NOx decrease while CO and VOCs increase with increasing altitude.
Zhang *et al.,* **2008**	Estimated vehicular emission inventories using dynamic EFs.	Total emission inventories of criteria pollutants & CO_2 grew continuously up to the year 2030.
Lents *et al.,* **2004**	Estimated & Compared key transportation parameters for seven cities worldwide using IVE model.	Higher average speed: lower EFs, more diesel cars: higher PM EFs, leaded fuel: catalyst ineffective.

2.6 Validation & Comparative Analysis

The uncertainty of estimates made by using emission models depend on the uncertainties in the model's internal parameters (EFs) and input data (Shorshani *et al.,* 2015) . The validation of predicted emission factors, obtained from emission models, is vital and has been done for IVE model to double-check the model EFs against real world data. This process of validation has become a common practice due to the extensive usage of PEMS (Franco *et al.,* 2013). This validation process has been reported by several studies including those conducted by independent researchers using technologies such as PEMS and remote sensing measurements. Studies conducted by ISSRC, measured averaged emissions (using PEMS) normalized to FTP driving cycles and then divided them by the emissions predicted by the IVE model for the purpose of comparison (Lents *et al.,* 2005; Lents *et al.,* 2007 b; Lents *et al.,* 2007 c). Measured emissions were taken on the LA4 cycle (which represents the hot running part of the FTP driving cycle).

Running CO_2 emissions predicted by IVE model were found in good agreement with measured emissions in Mexico City and Sao Paulo (Lents *et al.,* 2005), Istanbul (Lents *et al.,* 2007 a), and Xian (Tolvett *et al.,* 2008); however they were underestimated in Almaty (Lents *et al.,* 2007 c). Running NOx emissions were mostly underestimated by IVE model except for Beijing (Tolvett *et al.,* 2007). Running CO emissions predicted by IVE were overestimated for Beijing and underestimated for Mexico City (Lents *et al.,* 2005), Almaty (Lents *et al.,* 2007 c) and Xian (Tolvett *et al.,* 2008). PM emissions were overestimated by IVE model for Istanbul (Lents *et al.,* 2007 a) and Beijing (Tolvett *et al.,* 2007) but were found accurate for Xian (Tolvett *et al.,* 2008). Therefore, IVE model results generally did not showed any typical prejudice and were able to produce a considerably suitable estimation of vehicular emissions as compared to other methods. However, discrepancies such as these have been expected when IVE model was being developed and appropriate methods are also found to modify model's default emission factors thorough adjustment files in order to incorporate measured emissions (Lents *et al.,* 2005; Lents *et al.,* 2007 b; Tolvett *et al.,* 2007).

Another method used for the validation of IVE estimates has been the use of remote sensing measurements. In remote sensing, the idea of remotely measuring vehicle emissions emitted by a passing automobile was developed and implemented (Bishop *et al.,* 1989; Kuhns *et al.,* 2004). Guo *et al.* (2007 a) compared fuel-based exhaust emission inventories based on remote sensing measurements with IVE model estimates for Hangzhou (China), and found these inventories to be 45.5 per cent higher for CO, 6.6 per cent higher for HC, and 53.7 per cent lower for NOx, than those estimated by the IVE model. Another study also by Guo *et al.* (2007 b) used remote sensing measurements to assess IVE predictions, and reported emissions predicted by IVE model to be 37 per cent lower for CO, approximately equal for HC, and 113 per cent higher for NOx than remote sensing based measurements.

These studies have provided some promising results keeping in view the limitations of remote sensing technique such as its instantaneous approximation, inability to measure multiple traffic lanes, and the potential impact of testing location, time and driving behavior of vehicles (Sjodin and Lenner, 1995; Sadler *et al.,* 1996; Frey and Eichenberger, 1997; Franco *et al.,* 2013). The systematic difference between values of CO and NOx calculated by both approaches can be attributed to the effect of vehicle operation under fuel-rich conditions which is not considered in IVE model estimations (Guo *et al.,* 2007 b). In a study by Yu *et al.* (2009), a survey was conducted on the use of existing emission models in which nearly 90 per cent of the respondents, being transportation emission's professionals, specified that they use travel based emission models, and based on this survey IVE model was placed first in terms of operator friendliness and was given the highest overall evaluation.

Chapter 3

MATERIALS AND METHODS

3.1 Overall Methodology

Data collection was designed according to the guidelines described in the IVE manual ‘Field Data Collection Activities’ (ISSRC, 2014). Data was collected during a three month period from September to November, 2014. The data collection process consisted of two parts: (i) Primary data collection and (ii) Secondary data collection. Primary data collection for Islamabad city consisted of determining vehicle technology distribution via traffic video recordings and vehicle surveys, and determining the vehicle starting and driving patterns with the help of GPS data loggers. The overall research methodology adopted for this study is presented in Fig. 3.1.

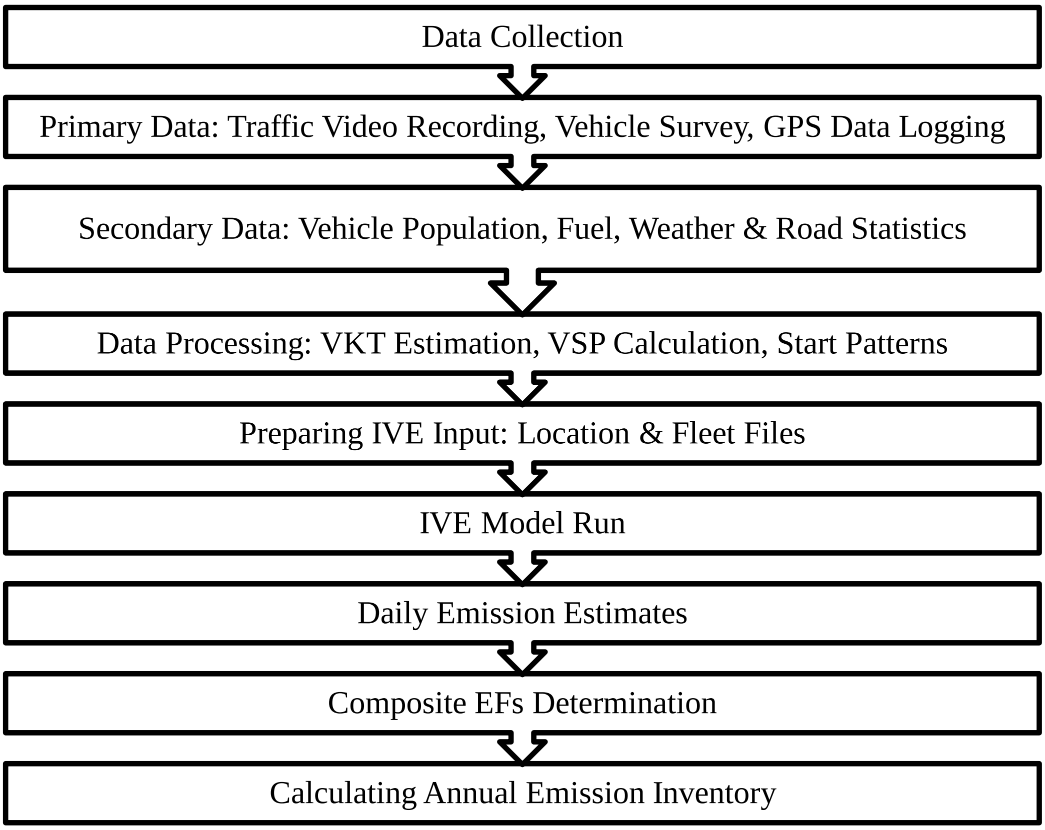

Fig. 3.1: Flow sheet of overall research methodology adopted

3.2 Vehicle Technology Distribution

Vehicle technologies operating on roads of Islamabad were determined in two steps. First step consisted of conducting traffic video recordings at selected roads in order to determine fractions of different on-road vehicle types and their hourly flow. This was supplemented by the second step of conducting a pre-defined questionnaire survey at different places within the city (mostly in the vicinity of video recording locations) in order to get a more representative data. City sectors were selected according to income and suitability of data acquisition by taking into consideration the ongoing construction of a mass transit bus project in the city that may have caused changes in the overall driving patterns. The points where video recordings were conducted are shown in Fig. 3.2.

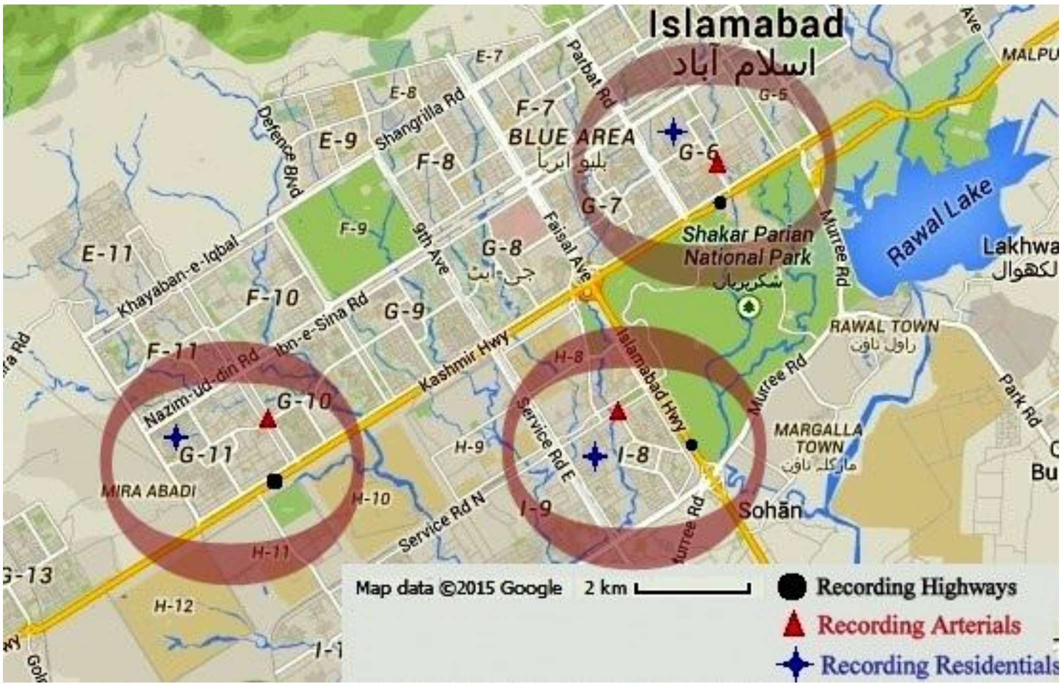

Fig. 3.2: Map of Islamabad showing points of video recordings (three selected sectors are circled)

3.2.1 Traffic Video Recording

Traffic at selected road types was videotaped, and analyzed at a later stage. Hourly vehicle flow was calculated along with the determination of fractions of different on-road vehicle technologies in the city. Three road types i.e. highway, arterial, and residential were selected for each of the three selected regions of Islamabad (Fig. 3.2). The I-8 sector area (mainly single and double story apartments) was selected for being dwelled by relatively higher income population class than G-6 sector (more commercial activity) while G-11 sector area was selected to represent the area dwelled by lower to middle class (a mix of multiple story apartments with two story houses). The video recording was done for 12 hours each day for six days (non-consecutive) from 0700 hours till 1900 hours. Each video recording period was of 20 minutes duration for every selected hour which was considered to represent the whole hour of interest. Detailed traffic video recording schedule is shown in Table 3.1.

Table 3.1: Schedule for traffic video recording at different locations of city

Time (Hours)	**Day 1 (Monday)**	**Day 3 (Wednesday)**	**Day 5 (Monday)**
0700-0800	Arterial near G11-West	Residential G6	Islamabad Highway i8
0800-0900	Residential G11	Kashmir Highway G6	Arterial near i8
0900-1000	Kashmir Highway G11	Arterial near G6	Residential i8
1000-1100	Arterial near G11-West	Residential G6	Islamabad Highway i8
1100-1200	Residential G11	Kashmir Highway G6	Arterial near i8
1200-1300	Kashmir Highway G11	Arterial near G6	Residential i8
	Day 2 (Tuesday)	**Day 4 (Thursday)**	**Day 6 (Tuesday)**
1300-1400	Arterial near G11-West	Residential G6	Islamabad Highway i8
1400-1500	Residential G11	Kashmir Highway G6	Arterial near i8
1500-1600	Kashmir Highway G11	Arterial near G6	Residential i8
1600-1700	Arterial near G11-West	Residential G6	Islamabad Highway i8
1700-1800	Residential G11	Kashmir Highway G6	Arterial near i8
1800-1900	Kashmir Highway G11	Arterial near G6	Residential i8

3.2.2 Vehicle Survey

To better understand different types of on-road vehicles, video recordings were supplemented by vehicle surveys. In total, 1430 vehicles were surveyed (750 passenger vehicles, 140 taxis, 110 vans and 430 motor cycles) with an almost 33 per cent share of each selected sector. In this survey, vehicles owners/drivers were asked to respond to a set of questions to find out vehicle registration years, odometer readings, manufacturers/models, assembly (local or imported), catalytic converters installed/operational or not, type of fuels used, fuel injection systems and Euro compliant emission standards for their vehicles. Local car dealers and mechanics were also consulted to understand the technical aspects of the vehicles for correct classification of vehicle technologies. The survey was conducted in the nearby parking areas where video recording was conducted to produce a representative data. Following the survey, vehicle age and aggregate odometer readings were processed for determining average age for all vehicle types and to establish annual vehicle usage i.e. VKT by regression analysis of odometer readings (km) versus vehicle age (years). For Taxis, however, an alternative approach (to regression analysis) was also used in which GPS data and survey data on daily Taxi use was combined to produce a per day driving activity. This was done due to the fact that most of the taxis were found with malfunctioning/ dysfunctional odometers.

3.3 Vehicle Starting Pattern

Since engine starts also contribute to exhaust emissions differently and sometimes more significantly than normal operation, number of vehicle starts in a day, and time between an engine switch-off and next startup (soak time) was also monitored using the GPS data that produced a 32 vehicle-days data for all vehicles types. An additional survey was also conducted to better quantify vehicle start distribution for these vehicle types. Soak time distribution in IVE model is represented in 10 groups with the first interval having soak period between 0 to 15 minutes (smallest soak time interval, warm start) and tenth interval having soak period of more than 18 hours (largest soak time interval, cold start). Soak time of less than 4 minutes was not considered as a vehicle start in calculating start patterns as done earlier in other studies (Kim Oanh *et al.,* 2012; Shrestha *et al.*, 2013).

3.4 Vehicle Driving Pattern

To determine driving patterns for passenger cars, taxis, vans and motor cycles, Global Sat GPS Data Logger (DG-200) was used. GPS data logger can store second by second vehicle velocity, location (latitude, longitude, and altitude) and corresponding local time. The GPS data logger was installed for one day (24 hours) in vehicles while they were operated in their normal routines. This includes 15 passenger cars, 5 taxis, 4 vans and 8 motorcycles. Except for taxis which were also found in making some trips in the neighboring city of Rawalpindi (this data was not used in our study), passenger cars, vans and motorcycles selected were mostly operated in Islamabad city. The selected volunteer drivers/owners for passenger cars and motorcycles belonged to different occupations (students, government/private employees, businessmen etc.) and for taxis and vans, drivers residing in different parts of city were selected, to ensure the randomness in data collection. Although driving patterns were recorded for a 24-hour interval, driving activity during late night hours (2300 to 0500 hours) was only observed for taxis. As all the vehicles were operated in their usual routines, all three road types were travelled and consequently processed to develop location files for IVE input. The obtained GPS data was then used to develop VSP bins required for IVE modeling calculated by the method developed by Jiménez (1999), details given in Eq. 3.1 below. There are 60 VSP bins distributed in three engine stress modes (calculated by Eq. 3.2) and each point of vehicle driving can be attributed to particular VSP bin.

$$VSP = v \times (a \times (1+ \varepsilon_i) + g \times grade + g \times C_R) + 0.5 \times \rho_a \times (C_D \times A)/m \times (v + v_w)^2 \times v$$

$$= v \times [1.1\, a + \{9.81 \times atan\, (sin\, (grade))\} + 0.132] + 0.000302 \times v^3 \qquad \text{(Eq. 3.1)}$$

Where,

VSP: vehicle specific power (kW/t);
v: vehicle speed (m/s);
v_w : headwind into the vehicle (~0 m/s);
ε_i: mass factor which is the equivalent translational mass of the rotating components (wheels, gears, shafts, etc.) of the power train (~0.1);
grade: vertical rise/slope length;
g: acceleration due to gravity (9.8 m/s^2);
a: vehicle acceleration (m/s^2);
C_R: coefficient of rolling resistance (dimensionless, ~0.0135);
C_D: aerodynamic drag coefficient;
A: Frontal area of the vehicle (m^2);
ρ_a: Ambient air density (1.207 kg/m^3 at 20°C);
m: vehicle mass (t)
$C_DA/m = 0.0005$ (m^2/t)

$$\text{Engine Stress (unit less)} = RPM_{index} + (0.08\ ton/kW) \times PreaveragePower \qquad \text{(Eq. 3.2)}$$

Where,

$PreaveragePower = Average\ (VSP_{t= -5\ sec\ to\ -25\ sec})$ (kW/ton)
And, $RPM_{index} = Velocity_{t=0}$ /SpeedDivider (unit less)

3.5 Secondary Data Collection

Secondary data required for input in the IVE model's location file was acquired from different sources and processed accordingly. This included fuel (petrol and diesel) characteristics and total registered vehicle population (by type) in Islamabad obtained from Hydrocarbon Development Institute of Pakistan (HDIP) and Excise & Taxation Department (Islamabad Capital Territory Administration, ICTA) respectively. Total road lengths in Islamabad for all three types were obtained from the directorate of Traffic Engineering and Transportation Planning (capital development authority, CDA). Temperature and relative humidity data were acquired from the Department of Atmospheric Science, University of Wyoming (http://weather.uwyo.edu/) for the last ten years and altitude was estimated based on GPS data. Since the study was undertaken in the last quarter of the year, meteorological data for the corresponding period was used in IVE modeling. The secondary data helps IVE model to modify default emission factors according to local conditions.

3.6 IVE Modeling

The data collection and analysis was followed by preparation of two input files for IVE model i.e. fleet and location file. The fleet file contains information on the types of on-road vehicle technologies (fuel, engine technology, emission controls and standards, mileage) and their respective share in overall fleet type along with fraction of such vehicles equipped with air conditioning. The location file contains more details on vehicle driving pattern, soak distribution, fuel characteristics, and meteorological information. All of the default pollutants in provided in IVE model were selected except for lead which has been phased out in Pakistan since 2005 (Faiz *et al.*, 2009). This includes criteria pollutants (CO, NOx, SOx, and PM), both exhaust and evaporative VOCs, toxic pollutants (1,3 butadiene, acetaldehyde, formaldehyde, ammonia (NH_3) and benzene) and GHGs (CO_2, nitrous oxide (N_2O) and CH_4).

In total, 12 location files and 4 fleet files were prepared for the considered vehicles types operated on three road types. The hourly and daily emissions for each of the 12 locations were calculated followed by an analysis of overall emissions by vehicle types, road types, and by time of the day. In the end, composite emission factors for running emissions (g km^{-1}) and start emissions (g $start^{-1}$) for individual vehicle types were also determined and analyzed.

RESULTS AND DISCUSSION

4.1 Video Recording Analysis

Out of the 36 hours (9 locations) where traffic was videotaped, 12 belonged to each road type. The results are summarized in Table 4.1 for all vehicle types observed and counted.

Table 4.1: Traffic video results for vehicles in Islamabad (monitoring: 0700-1900 hours)

	Highway	**Arterial**	**Residential**	**Overall Islamabad**
Road Share (%)	0.57	16.23	83.19	-
Driving Share (%)	4.40	44.75	50.85	-
Vehicles/hour	3,621	1292	287	883.21
Passenger Cars (%)	57.66	64.43	43.92	53.70
Taxis (%)	6.83	5.30	6.63	5.04
Vans (%)	5.25	6.39	3.23	4.93
Motorcycles (%)	28.17	22.39	41.07	32.54
Others (%) *	2.09	1.49	5.15	3.88

* Including buses and trucks (small, medium & large) & off-road vehicles which were counted in the study.

Average hourly vehicle flow was 3621 (min: 1125, max: 5286) on highways, 1292 (min: 840, max: 1798) on arterials, and 287 (min: 101, max: 569) on residential roads. Data provided by the directorate of Transport and traffic engineering (Islamabad) shows that only 0.57 per cent (265km) of the roadway length is highways, 16.2 per cent (7850 km) is arterials and remaining 83.2 per cent (38750 km) is residential. Based on the weighted average of vehicle flow found in traffic video analysis against the share of individual road types, it was estimated that the 4.4 per cent of the driving activity in Islamabad city is on highways, 44.8 per cent on arterials and 50.8 per cent on residential roads. The weighted averages based on activity share of the three road types showed that private passenger cars represent 53.7 per cent of the overall on-road vehicle fleet of Islamabad, followed by 5 per cent taxis, 4.9 per cent vans and 32.5 per cent motorcycles and all these vehicle types combined accounted for 96.1 per cent of city’s on-road fleet. This is in agreement with the data provided for total vehicles registered in Islamabad except for the taxis which were significantly higher in traffic video results than registered on papers. The main reason observed was that most taxis come to operate in Islamabad that are registered in other cities especially from the neighboring city of Rawalpindi causing significant increase in its share as observed.

Passenger cars and vans had shares of 64.4 per cent and 6.4 per cent on arterials (highest) and 43.9 per cent and 3.2 per cent on residential roads (lowest) respectively. Taxis had a share of 6.8 per cent on highways (highest) and 5.3 per cent on arterials (lowest). For motorcycles, their share was 41.1 per cent on residential roads (highest) and 22.4 per cent on arterials (lowest). The highest driving activity was observed in both morning rush hours (8-10 am) and evening rush hours (4-6 pm) for all vehicles types. Vehicle flow per hour on three road types along with overall vehicle flow (weighted against driving share of each road type) for Islamabad is shown in Fig. 4.1.

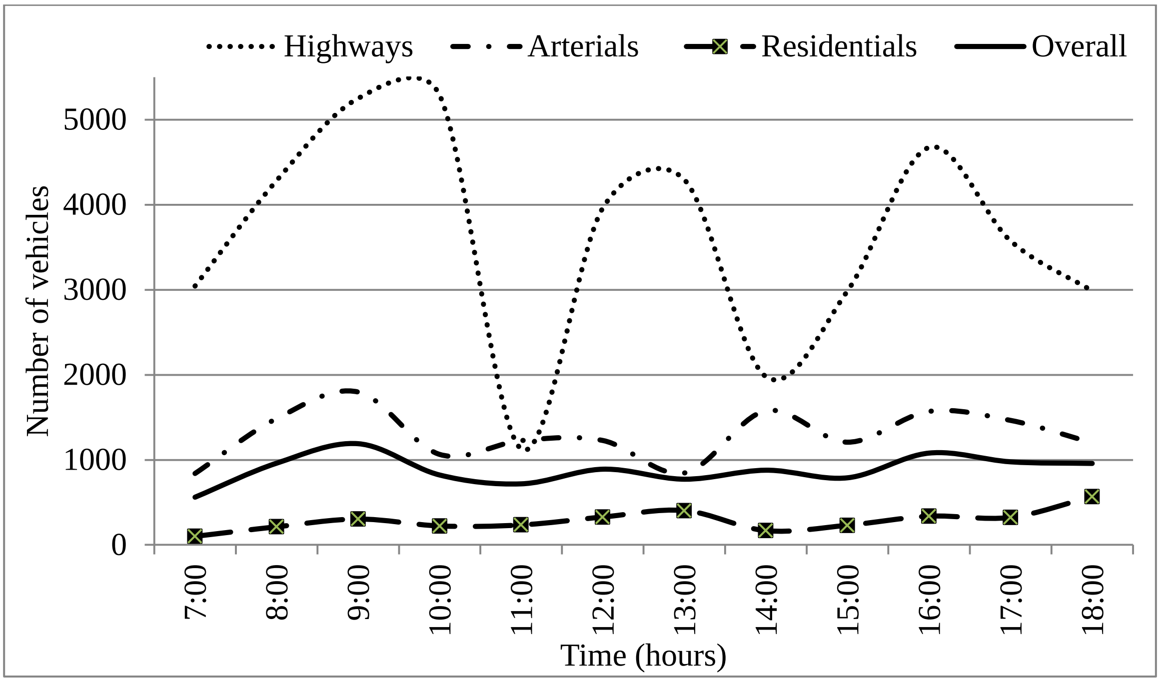

Fig. 4.1: Overall vehicle flow per hour and for three road types

(monitoring: 0700-1900 hours)

4.2 Vehicle Technologies, Survey Results & VKT

Surveys conducted were processed and analyzed to identify Vehicle technologies operating on the roads of Islamabad and matched to default IVE index vehicles, followed by VKT determination. The detailed survey results are discussed in the following sections.

4.2.1 Passenger Cars

Of the surveyed passenger vehicles, 85 per cent were using gasoline, 7.1 per cent were being operated on CNG (though 34.8 per cent of all passenger cars were found to be equipped with CNG kits but due to CNG shortages and longer queues at CNG filling stations, its usage was significantly low), 6.9 per cent vehicles were diesel operated, whereas only 1 per cent of vehicles were found to be hybrid cars. Air conditioning was found in 81 per cent vehicles and 71.2 per cent were found to be locally manufactured or assembled vehicles. Largest manufacturer was Suzuki with a share of 41.2 per cent followed by Toyota (33.5 per cent), Honda (12.8 per cent), Daihatsu (3 per cent) and

Hyundai (2.7 per cent). Vehicles with Multi-Point Fuel Injection (MPFI) system had the largest share (68.3 per cent) followed by carbureted vehicles (22.3 per cent). With respect to IVE technology indices, index 100 had the greatest share (13.4 per cent), followed by other index vehicles such as index 180 (11 per cent), index 99 (9.6 per cent), index 198 (7.6 per cent) and index 01 (7.1 per cent). Detailed IVE index list for passenger cars is presented in Table 4.2.

Average age of passenger cars was found to be 7.97 years with 34 per cent vehicles less than 5 years old, 37 per cent vehicles between ages 5-10 years, 17 per cent vehicles between the age 10-15 years and only 12 per cent vehicles older than 15 years. This average age was lower than Nairobi (13.4) (GSSR, 2002), Almaty (11.3) (GSSR, 2003) and Lima (11.0) (Lents *et al.,* 2004 b) but higher than other cities such as Pune (4.7) (GSSR, 2004), Beijing (4.03) (Huan *et al.,* 2005) and Shanghai (3.61) (Huang *et al.*, 2005).

4.2.2 Taxis

Among the surveyed taxis, 81 per cent were using gasoline and 19 per cent were being operated on CNG (though 69.8 per cent of all taxis were equipped with CNG kits). Air conditioning was installed in 7 per cent taxis and all of taxis were found to be locally manufactured or assembled with Suzuki having the vast share of 98 per cent. Taxis with carbureted engines had the overwhelming share (95 per cent) whereas only a small fraction of taxis (5 per cent) had MPFI system which is also consistent with fewer Euro II taxis (4 per cent) observed (while the rest did not comply with any of the Euro standards). With respect to IVE technology indices, index 2 had the greatest share (62.8 per cent), followed by index 218 (15.5 per cent), index 01 (7.8 per cent), index 0 (6.2 per cent), and index 180 (3.1 per cent) respectively as shown in Table 4.3.

Table 4.2: Details of matched IVE index Passenger Cars with their respective share

IVE Index	Description of technologies	% Share
0	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : <79K km	6.70
1	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : 80-161K km	7.13
2	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : >161K km	3.71
46	Pt: Auto/Sm Tk : Lt : SgPt FI : none : PCV : 80-161K km	1.57
47	Pt: Auto/Sm Tk : Lt : SgPt FI : none : PCV : >161K km	0.86
99	Pt: Auto/Sm Tk : Lt : MPFI : none : PCV : <79K km	9.56
100	Pt: Auto/Sm Tk : Lt : MPFI : none : PCV : 80-161K km	13.41
101	Pt: Auto/Sm Tk : Lt : MPFI : none : PCV : >161K km	2.00
102	Pt: Auto/Sm Tk : Med : MPFI : none : PCV : <79K km	1.28
103	Pt: Auto/Sm Tk : Med : MPFI : none : PCV : 80-161K km	3.71
104	Pt: Auto/Sm Tk : Med : MPFI : none : PCV : >161K km	0.71
106	Pt: Auto/Sm Tk : Hv : MPFI : none : PCV : 80-161K km	0.57
180	Pt: Auto/Sm Tk : Lt : MPFI : EuroII : PCV/Tank : <79K km	10.98
181	Pt: Auto/Sm Tk : Lt : MPFI : EuroII : PCV/Tank : 80-161K km	1.71
182	Pt: Auto/Sm Tk : Lt : MPFI : EuroII : PCV/Tank : >161K km	0.57
183	Pt: Auto/Sm Tk : Med : MPFI : EuroII : PCV/Tank : <79K km	2.57
184	Pt: Auto/Sm Tk : Med : MPFI : EuroII : PCV/Tank : 80-161K km	1.85
198	Pt: Auto/Sm Tk : Lt : MPFI : EuroIV : PCV/Tank : <79K km	7.56
199	Pt: Auto/Sm Tk : Lt : MPFI : EuroIV : PCV/Tank : 80-161K km	2.43
201	Pt: Auto/Sm Tk : Med : MPFI : EuroIV : PCV/Tank : <79K km	2.43
202	Pt: Auto/Sm Tk : Med : MPFI : EuroIV : PCV/Tank : 80-161K km	1.43
210	Pt: Auto/Sm Tk : Med : MPFI : Hybrid : PCV/Tank : <79K km	0.57
216	NGrt: Auto/SmTk : Lt : Carb/Mx : None : PCV : <79K km	3.00
217	NGrt: Auto/SmTk : Lt : Carb/Mx : None : PCV : 80-161K km	2.57
218	NGrt: Auto/SmTk : Lt : Carb/Mx : None : PCV : >161K km	0.86
760	Ds: Auto/Sm Tk : Med : Dir-Inj : EGR+Improv :None :80-161Kkm	2.43
761	Ds: Auto/Sm Tk : Med : Dir-Inj : EGR+Improv : None : >161K km	1.14
813	Ds: Auto/Sm Tk : Med : FI : EuroIV : None : <79K km	1.28

Where, Pt: petrol, Ds: diesel, SmlEng: small engine, Lt: light. Med: medium, Hv: heavy, Carb: carburetor, PCV: positive crankshaft ventilation, FI: fuel injection, SgPt FI: single point fuel injection, MPFI: multi point fuel injection, EGR: exhaust gas recirculation, 3Wy: 3-way catalyst, Dir-Inj: direct injection, 2Cyc: 2 cycle, 4Cyc: 4 cycle

Note: technologies with a share less than 0.5 per cent are not shown here.

Table 4.3: Details of matched IVE index Taxis with their respective share

IVE Index	Description of technologies	% Share
0	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : <79K km	6.20
1	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : 80-161K km	7.75
2	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : >161K km	62.79
47	Pt: Auto/Sm Tk : Lt : SgPt FI : none : PCV : >161K km	0.78
180	Pt: Auto/Sm Tk : Lt : MPFI : EuroII : PCV/Tank : <79K km	3.10
181	Pt: Auto/Sm Tk : Lt : MPFI : EuroII : PCV/Tank : 80-161K km	0.78
216	NGrt: Auto/SmTk : Lt : Carb/Mx : None : PCV : <79K km	1.55
217	NGrt: Auto/SmTk : Lt : Carb/Mx : None : PCV : 80-161K km	1.55
218	NGrt: Auto/SmTk : Lt : Carb/Mx : None : PCV : >161K km	15.50

Average age of taxis was found to be 20.37 years with only 11 per cent taxis less than 5 years old, 19 per cent taxis between the age 5-15 years and 70 per cent taxis older than 15 years. This taxi fleet was significantly older than taxis in Kathmandu (9.5 years) (Shrestha *et al.,* 2013) and Beijing (4.9 years) (Huan *et al.,* 2005).

4.2.3 Vans

Vans are mostly used to carry 10 to 16 passengers and operated during 0600 to 2300 hours in most cases and are a significant mean of transportation for local public. It was found that 87 per cent of them were using gasoline, while 13 per cent were being operated on diesel. CNG use was not detected (although 45 per cent of them had CNG kits fitted) due to the reasons discussed earlier. Air conditioning was found in 41 per cent, and 53 per cent were found to be locally manufactured or assembled with Toyota and Suzuki having the major share of 63 per cent and 34 per cent respectively. Vans with MPFI system had the large share (53 per cent) whereas carbureted engines were also significant (29 per cent). Euro IV vans were quite low (10 per cent), Euro II vans were relatively higher (21 per cent). With respect to IVE technology indices, index 1 had the greatest share (13.8 per cent), followed by index 0 (12 per cent), index 103 (10 per cent), index 104 (6.4 per cent), and index 184 (6.4 per cent) as detailed in Table 4.4.

Table 4.4: Details of matched IVE index Vans with their respective share

IVE Index	Description of technologies	% Share
0	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : <79K km	11.93
1	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : 80-161K km	13.76
2	Pt: Auto/Sm Tk : Lt : Carb : None : PCV : >161K km	3.67
49	Pt: Auto/Sm Tk : Med : SgPt FI : none : PCV : 80-161K km	1.83
50	Pt: Auto/Sm Tk : Med : SgPt FI : none : PCV : >161K km	1.83
102	Pt: Auto/Sm Tk : Med : MPFI : none : PCV : <79K km	5.50
103	Pt: Auto/Sm Tk : Med : MPFI : none : PCV : 80-161K km	10.09
104	Pt: Auto/Sm Tk : Med : MPFI : none : PCV : >161K km	6.42
180	Pt: Auto/Sm Tk : Lt : MPFI : EuroII : PCV/Tank : <79K km	4.59
183	Pt: Auto/Sm Tk : Med : MPFI : EuroII : PCV/Tank : <79K km	5.50
184	Pt: Auto/Sm Tk : Med : MPFI : EuroII : PCV/Tank : 80-161K km	6.42
185	Pt: Auto/SmTk : Med : MPFI: EuroII : PCV/Tank : >161K km	4.59
201	Pt: Auto/Sm Tk : Med : MPFI : EuroIV : PCV/Tank : <79K km	4.59
202	Pt: Auto/Sm Tk : Med : MPFI : EuroIV : PCV/Tank :80-161K km	5.50
743	Ds: Auto/SmTk : Med : Pre-Inj : None : None : >161K km	2.75
759	Ds: Auto/SmTk : Med : Dir-Inj : EGR+Imp. : None :>161K km	0.92
760	Ds: Auto/SmTk : Med : Dir-Inj:EGR+Imp.:None :80-161K km	3.67
761	Ds: Auto/SmTk : Med : Dir-Inj : EGR+Improv None :>161K km	2.75
796	Ds: Auto/SmTk : Med : FI : EuroII : None : 80-161K km	1.83
813	Ds: Auto/SmTk : Med : FI : EuroIV : None : <79K km	1.83

Average age of vans was found to be 10.5 years with 20 per cent vans less than 5 years old, 50 per cent vans between the age 5-10 years, 7 per cent vans between the age 10-15 years, and 23 per cent vans older than 15 years. This average age for vans was higher than that of Kathmandu (8.7 years) (Shrestha *et al.*, 2013).

4.2.4 Motorcycles

Of the surveyed motorcycles, all were petrol fueled with 97 per cent either manufactured or assembled locally. Among different manufacturers, Honda had the highest share of 45 per cent followed by Hero (16 per cent), Yamaha (8 per cent), Habib (3 per cent) etc. Motorcycles with 4-stroke engines had the overwhelming share of 96 per cent with the remaining 4 per cent had 2-stroke engines. In motorcycle fleet, 22 per cent conformed to Euro 2 standards (mainly those manufactured locally since Euro 2 implementation). With respect to IVE technology indices, index 1207 had the greatest share (23 per cent), followed by index 1206 (21 per cent), index 1208 (17 per cent), index 1215 (10.8 per cent), and index 1211 (6.8 per cent). Details can be seen in Table 4.5.

Average age of motorcycles was found to be 6.34 years with 58 per cent motorcycles less than 5 years old, 25 per cent between the age 5-10 years, 7 per cent motorcycles between the age 10-15 and only 10 per cent motorcycles older than 15 years. The average motorcycle age was higher than that in Kathmandu (4.3 years) (Shrestha *et al.,* 2013) and Hanoi (3.6 years) (Kim Oanh *et al.*, 2012). Detailed vehicle distribution for all vehicle types with respect to age in years is shown in Fig. 4.3.

Table 4.5: Details of matched IVE index Motorcycles with their respective share

IVE Index	Description of technologies	% Share
1170	Pt: SmlEng : Lt : 2Cyc : None : None: <25K km	0.25
1172	Pt: SmlEng : Lt : 2Cyc : None : None: >50K km	0.50
1175	Pt: SmlEng : Med : 2Cyc : None : None: >50K km	2.25
1179	Pt: SmlEng : Lt : 2Cyc : Improved : None: <25K km	0.50
1180	Pt: SmlEng : Lt : 2Cyc : Improved : None: <25K km	0.50
1206	Pt: SmlEng : Lt : 4Cyc Carb : None : None: <25K km	21.0
1207	Pt: SmlEng : Lt : 4Cyc Carb : None : None: 26-50K km	22.5
1208	Pt: SmlEng : Lt : 4Cyc Carb : None : None: >50K km	17.0
1209	Pt: SmlEng : Med : 4Cyc Carb : None : None: <25K km	2.50
1210	Pt: SmlEng : Med : 4Cyc Carb : None : None: 26-50K km	3.25
1211	Pt: SmlEng : Med : 4Cyc Carb : None : None: >50K km	6.75
1214	Pt: SmlEng : Hv : 4Cyc Carb : None : None: >50K km	1.0
1215	Pt: SmlEng : Lt : 4Cyc Carb : Improved : None: <25K km	10.75
1216	Pt: SmlEng : Lt : 4Cyc Carb : Improved : None: 26-50K km	1.0
1218	Pt: SmlEng : Med : 4Cyc Carb : Improved : None: <25K km	1.75
1219	Pt: SmlEng : Med : 4Cyc Carb : Improved : None: 26-50K km	0.25
1227	Pt: SmlEng : Med : 4Cyc Carb : High Tech : None: <25K km	3.75
1228	Pt: SmlEng : Med : 4Cyc Carb : High Tech : None: 26-50K km	0.50
1234	Pt: SmlEng : Lt : 4Cyc Carb : Catalyst : None: 26-50K km	0.25
1235	Pt: SmlEng : Lt : 4Cyc Carb : Catalyst : None: >50K km	0.50
1236	Pt: SmlEng : Med : 4Cyc Carb : Catalyst : None: <25K km	1.75
1237	Pt: SmlEng : Med : 4Cyc Carb : Catalyst : None: 26-50K km	0.50
1248	Pt: SmlEng : Hv : 4Cyc FI : Catalyst : PCV: <25K km	0.75
1250	Pt: SmlEng : Hv : 4Cyc FI : Catalyst : PCV: >50K km	0.25

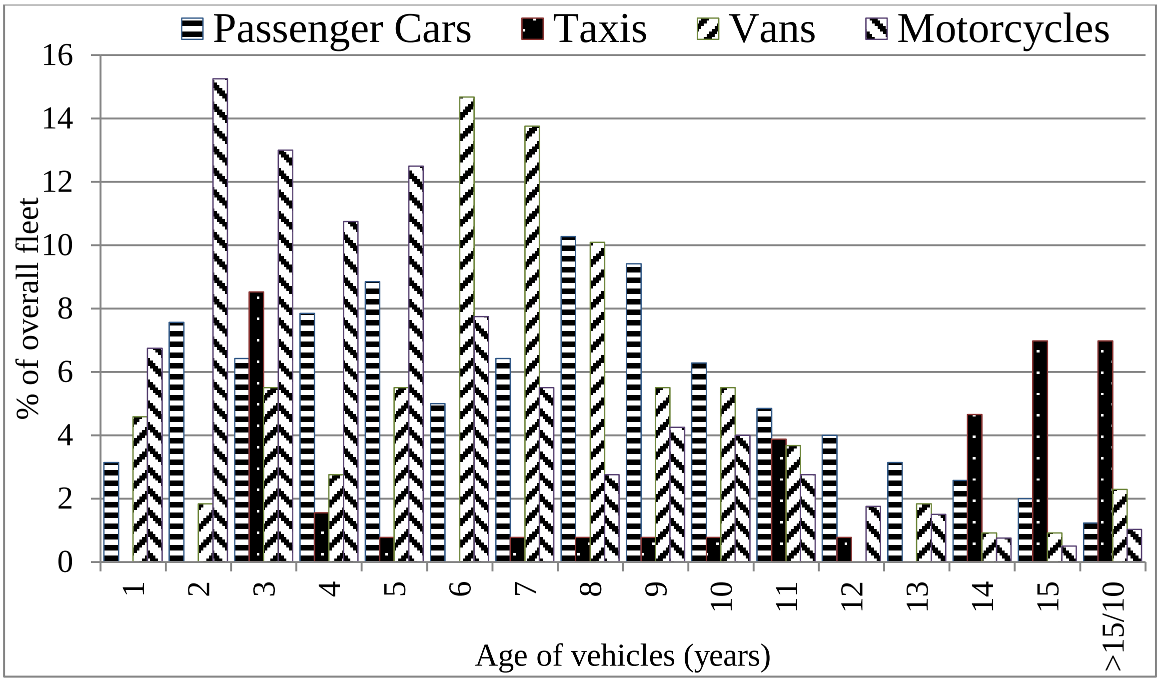

Fig. 4.2: Age distribution for vehicles in Islamabad (percentages of vehicles older than 15 years are divided by 10 for displaying purpose)

4.2.5 VKT Analysis

To calculate the VKT for each of the considered vehicle types, the respective age of each vehicle type (in years) was plotted on x-axis against the odometer readings (in kilometers) on y-axis and second degree least square fit was done to fit the data as shown in Figures 4.3 – 4.6. Average vehicle age was used to determine the average distance travelled by the vehicle using the second degree equation. Consequently, on average, kilometers travelled annually were calculated by substituting vehicle age as ±0.5 years in the respective second degree equations.

The annual driving for passenger cars was found to be 7474 km (20.5 km/day), 12046 km for vans (33.0 km/day), and 5306 km for motorcycles (14.5 km/day). However for taxis, regression analysis results showed annual driving of 81029 km (222 km/day) which appeared to be less accurate considering average taxi age of 20.37 years and high uncertainty in odometer reading of older taxis. By using another approach for taxis, GPS data and survey data on daily taxi use was combined to produce a per day driving activity. Survey results showed a per day driving of 91.7 km whereas GPS data showed a per day driving of 145.5 km. Thus average value of the later approach was used in IVE modeling which gives a per day driving equal to 118.6 km (43286 km/year). This translates into a total daily VKT share of 45.6%, 28%, 7.4%, and 18.9% for passenger cars, taxis, vans and motorcycles respectively.

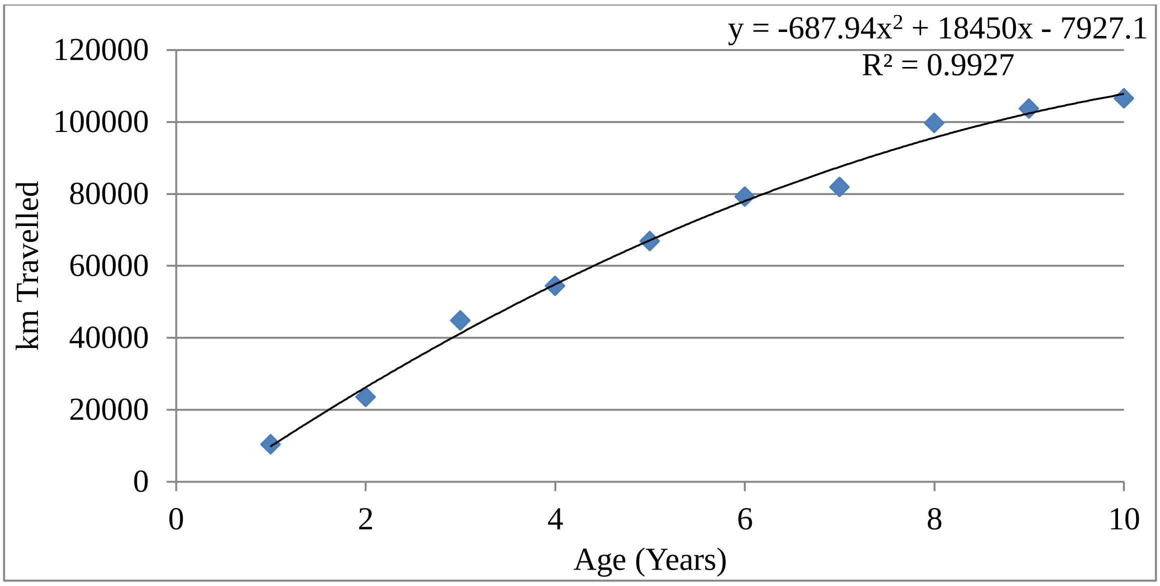

Fig. 4.3: Passenger car age vs. odometer readings

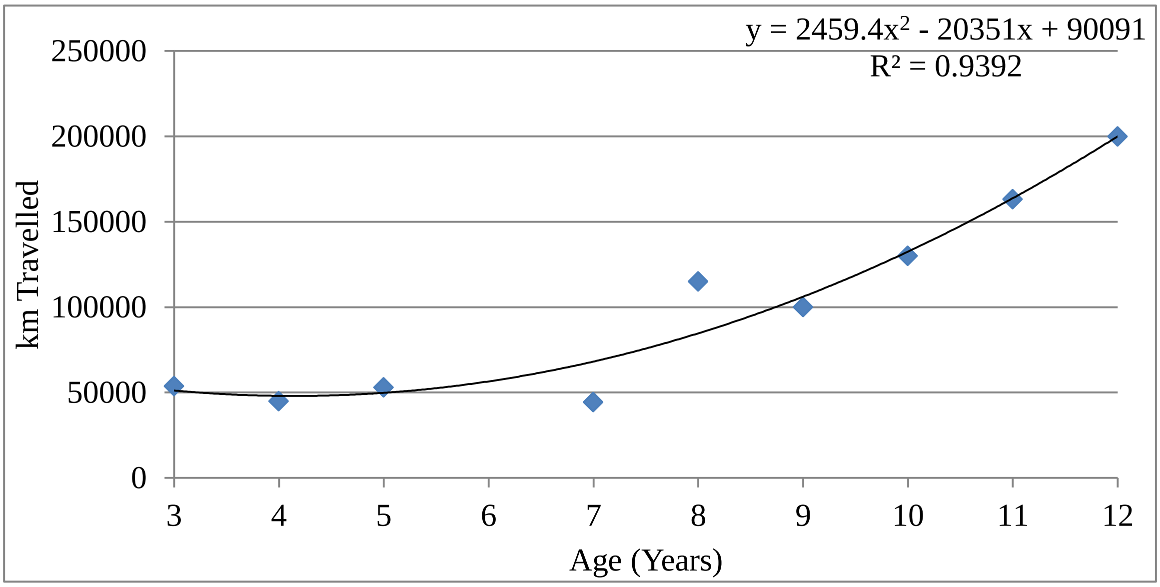

Fig. 4.4: Taxi age vs. odometer readings

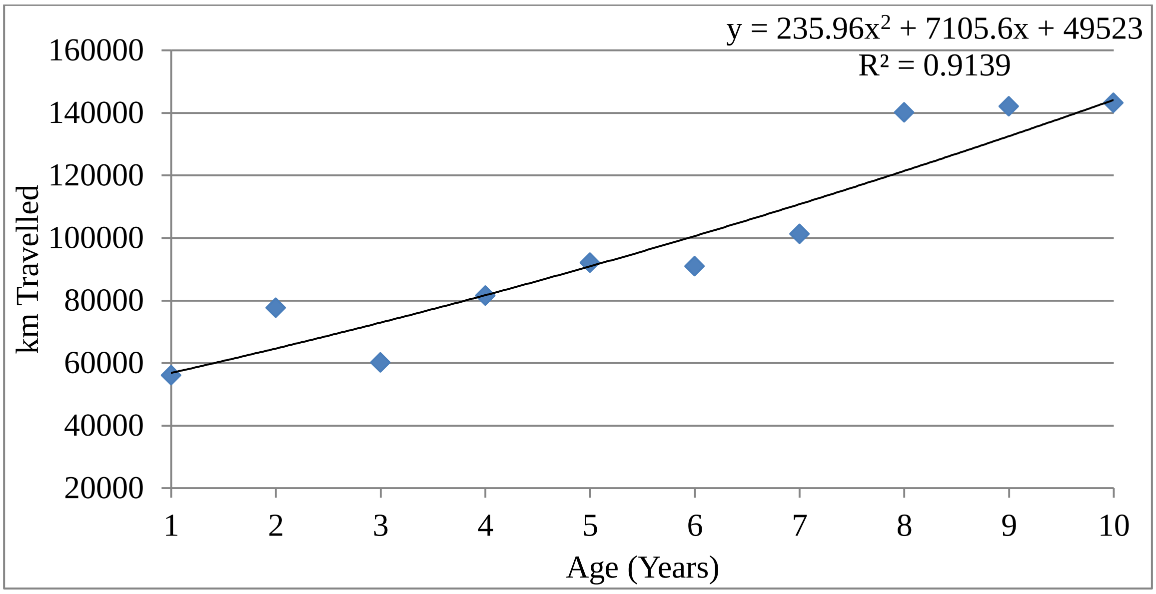

Fig. 4.5: Van Age vs. Odometer Readings

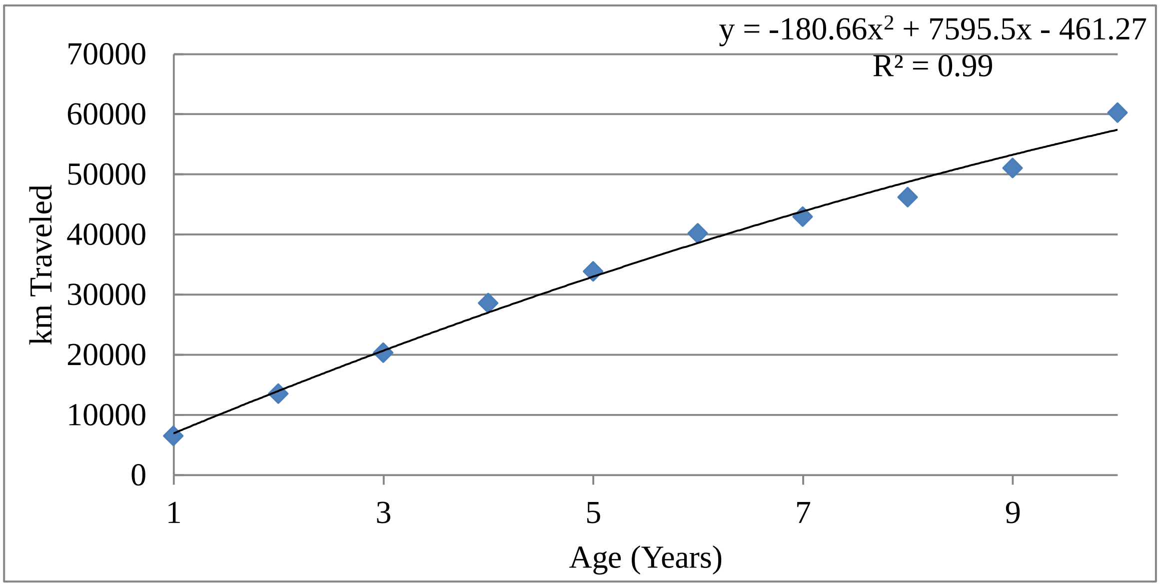

Fig. 4.6: Motorcycle age vs. odometer readings

4.3 Vehicle Starting Patterns

Number of daily startups and their distribution (soak pattern) was determined with the help of survey and GPS data. Analysis of data showed that on average, a passenger car is started about 5.9 times a day making 3.6 per cent startups on highways, 30.1 per cent startups on arterials and 66.3 per cent startups on residential roads. These startups per day were lower than Pune (7.02) (GSSR, 2004), Sao Paulo (6.1) (Lents *et al.*, 2004 c), and Beijing (6.7) (Huan *et al.*, 2005) but higher than Lima (5.6) (Lents *et al.*, 2004 b), Mexico

City (5.6) (Davis *et al.*, 2004), and Shanghai (5.2) (Huang *et al.*, 2005). The high number of startups on residential roads is because larger share of residential roads in the city and the fact that many workplaces together with residential apartments are located along these roads. Soak bin 1 (4-15 minutes) had the highest share (26.5 per cent) followed by soak bin 2 (16-30 minutes, 14.5 per cent), thus combined share of soak bins 1-3 was more than half. Soak bins 4-7 (intermediate soaks) had a combined share of 28.9 per cent while soak bins 8-10 had a combined share of 18.1 per cent which is low but these bins give off more emissions as the engine is cooled off as compared to soak bins 1, 2 and 3 (warm startups).

Similarly, a taxi was started about 13.6 times a day with 19.1 per cent, 54.4 per cent and 26.5 per cent of startups taking place on highways, arterials and residential roads respectively. The higher number of startups on arterial is due to the fact that most taxis take passengers from these arterial roads and they queue up on these roads as well to wait for new passengers. Soak bin 1 had the highest share (45.6 per cent) followed by soak bin 2 (17.7 per cent), thus combined share of soak bins 1-3 was more than three quarters (77.9 per cent). Soak bins 4-7 and 8-10 had combined shares of 16.2 per cent and 5.9 per cent respectively which indicate that taxis operate round the clock with minimal long soak times.

A van on average started 9.7 times a day with 15.5 per cent of startups taking place on highways and 58.6 per cent and 25.9 per cent on arterials and residential roads respectively. These daily startups are lower than those observed in Kathmandu (10.3) (Shrestha *et al.*, 2013) probably because of slightly longer van routes in Islamabad. The higher number of starts on arterials is similar to taxis as these vans make normal stops on these roads and pick new passengers from there. Soak bin 1 had the highest share (58 per cent) followed by soak bin 2 and bin 3 with each having a share of 12 per cent, thus combined share of soak bins 1-3 was overwhelming (82 per cent). Soak bins 4-7 and soak bins 8-10 had a share of 9 per cent each indicating that longer soaks were less frequent for vans similar to that of taxis. Fig. 4.7 shows the distribution of soak times for all vehicle types studied.

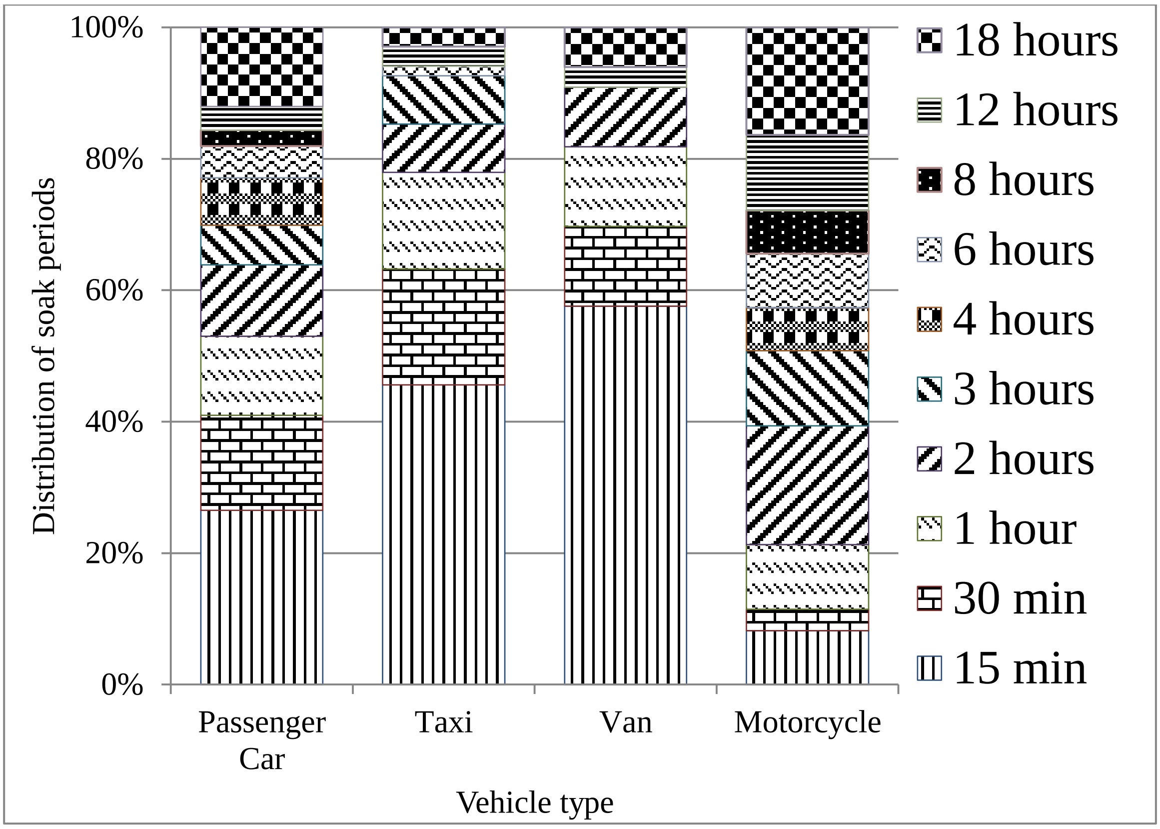

Fig. 4.7: Soak time distribution for all vehicles

Likewise, a motorcycle on average was started about 4.07 times a day with 2 per cent of these starts occurring on highways, 41 per cent on arterials and 57 per cent on residential roads. These daily number of startups are lower than Hanoi (4.9), Bangkok (4.43) (Kim Oanh *et al.,* 2012) and Pune (7.18) (GSSR, 2004) but greater than Kathmandu (3.8) (Shrestha *et al.,* 2013).

This shows that motorcycles and passenger cars both make higher number of starts on residential roads and lower number of starts on highways. For motorcycles, soak bins 1-3 had the combined share of 21.3 per cent, Soak bins 4-7 and Soak bins 8-10 had combined shares of 44.3 per cent and 34.4 per cent respectively.

4.4 Vehicle Driving Pattern

Driving patterns are an important indicator of local driving conditions along with region specific driving habits. With the help GPS data, different vehicle types were studied for all three road types and processed accordingly to prepare IVE location input files for these road types.

4.4.1 Average Trip Duration

Trip duration (or time of trips when vehicle was operated and running on the roads in usual routines) was monitored and analyzed by grouping them in three tiers for simplicity. For passenger cars, average trip duration was 14 minutes (min: 1, max: 67). Trips of less than 16 minutes had a major share of 64 per cent, trips of 16-30 minutes duration had a share of 27 per cent while trips of more than 30 minutes were rare (9 per cent). For taxis, average trip time was 25 minutes (min: 2, max: 111) and trips of less than 16 minutes had a nearly half share of 46 per cent, trips of 16-30 minutes and more than 30 minutes were high too (27 per cent each).

For vans, average trip time was 40 minutes (min: 1, max: 102) and trips of less than 16 minutes had a share of 30 per cent, trips of 16-30 minutes were less frequent (9 per cent) while trips of more than 30 minutes were significant (61 per cent). The higher trip time of vans as compared to taxis was mainly because vans were driven on longer routes within the city and they mostly made 1-2 minutes stops to pick/drop passengers. For motorcycles, average trip time was 17 minutes (min: 1, max: 47) and trips of less than 16 minutes had a large share of 65 per cent, trips of 16-30 minutes duration had a share of 21 per cent while trips of more than 30 minutes were less (14 per cent) implying that people do not frequently use motorcycles for longer journeys.

4.4.2 Average Speed

Average speed was also highly dependent on driving conditions (times of the day, congestion, road condition, road type etc.) and driving behavior. As expected, average speed was highest on highways and lowest on residential roads. Average speed of all 4 vehicle types are shown in Table 4.6 and hourly variation in average speed on three road types is shown in Figures 4.8 – 4.10.

Table 4.6: Overall average speed for all vehicles (km hr^{-1})

Vehicle Type	Highway	Arterial	Residential
Passenger Car	50.0	32.8	18.5
Taxi	44.7	29.2	16.6
Van	42.7	21.0	16.7
Motorcycle	40.6	26.3	18.1

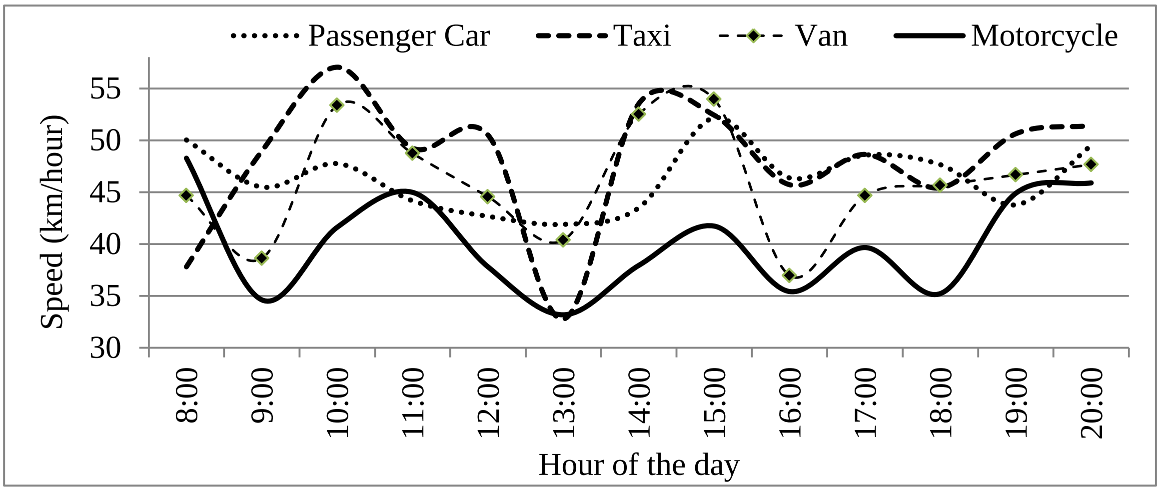

Fig. 4.8: Average speed on highways

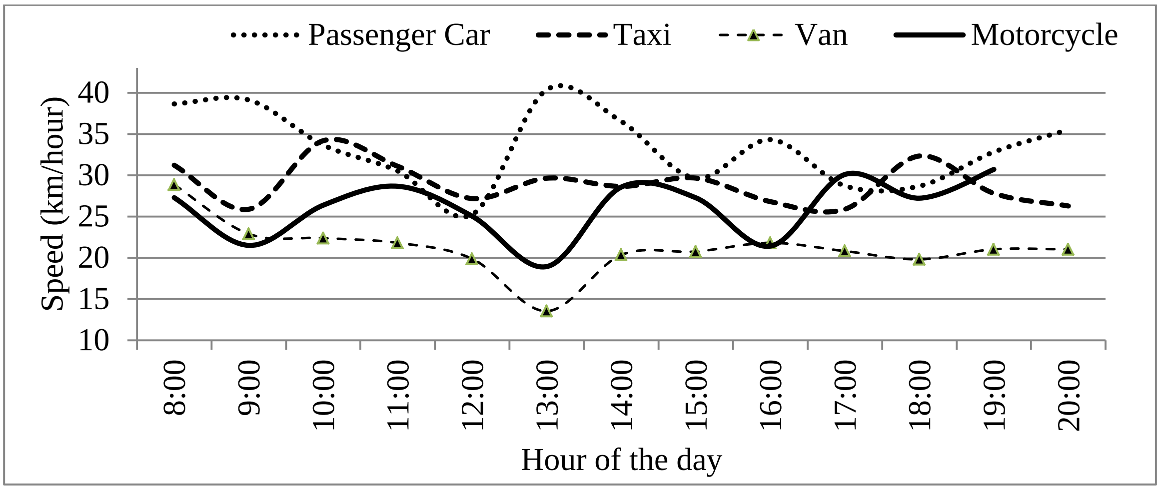

Fig. 4.9: Average speed on arterials

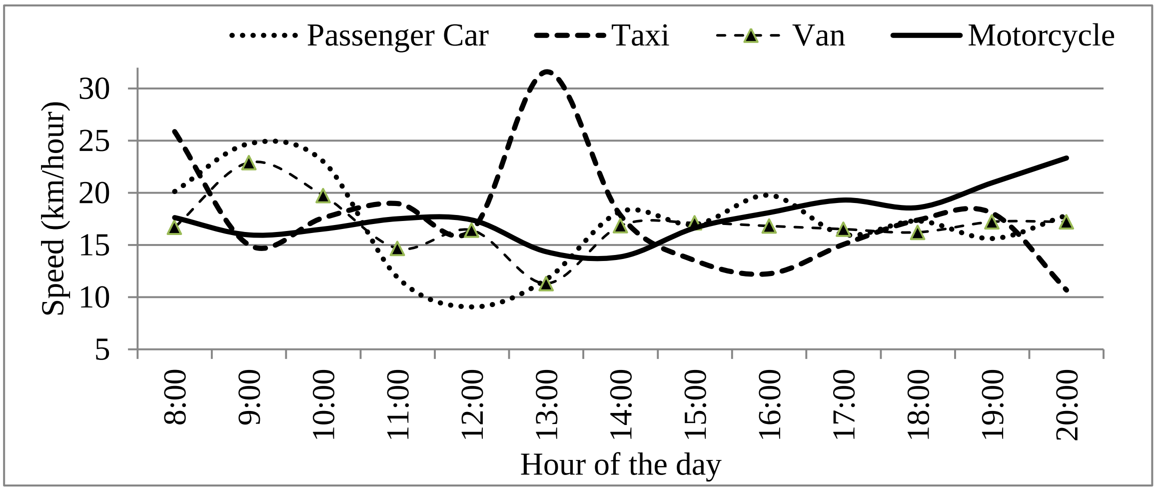

Fig. 4.10: Average speed on residential roads

4.4.3 VSP Distribution

From three engine stress modes, low stress mode (unit less) represents conditions where vehicle is operated under lower speeds and accelerations over a time span of 20 seconds (consecutive) with a relatively lower engine Revolutions per Minute (RPM), whereas high engine stress mode represents vehicle activity with higher speeds and accelerations for the last 20 seconds of operation with higher RPM (ISSRC, 2014). Major share of low engine stress mode (having VSP distribution lying between bins 0 to 19) was observed for all vehicle types on each road category which accounted for 97.4% for passenger cars, 97.7% for taxis, 98.8% for vans and 97.2% for motorcycles.

VSP bin number 11 which lies in the lower engine stress mode, had the highest share of driving on all three road types for all considered vehicle types followed by bin 12 except for motorcycles running on highways where bin 11 and 12 had a share of 22.2% and 30.1% respectively. Bins 1 to 11 represent conditions of negative power where vehicle is idling, slowing down (due to congestion or traffic signals) or going down a hill or combination of more than one of the conditions. Bin 12 represents conditions of zero or very low power situation such as waiting at a traffic signal while bin 13 and above represent the positive power where a vehicle is operating at a constant speed, accelerating, going up a hill or combination of these conditions (Lents *et al.*, 2004 c; Shrestha *et al.*, 2013). VSP bins in Islamabad are summarized in Figures 4.11 – 4.15.

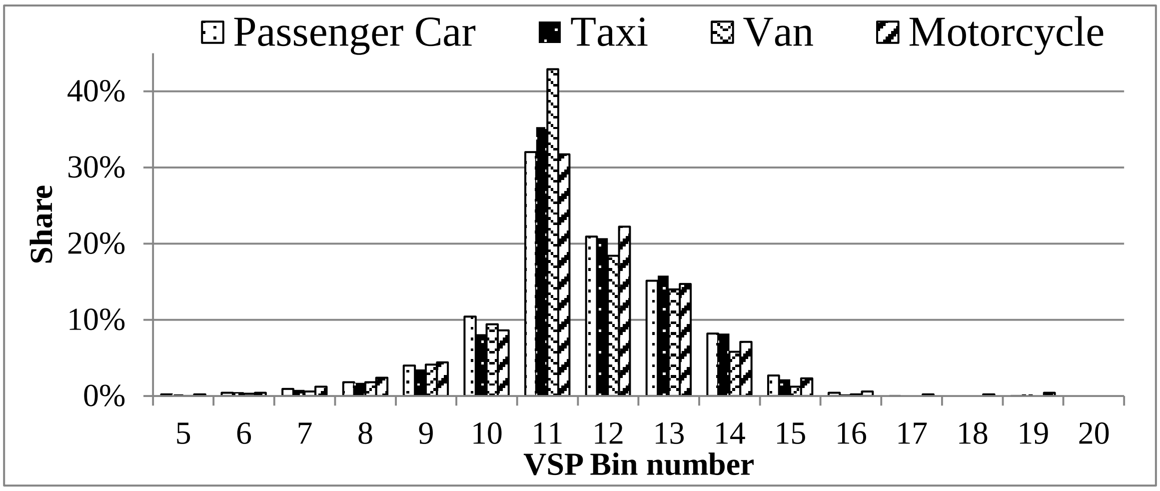

Fig. 4.11: VSP Share for all Vehicle Types

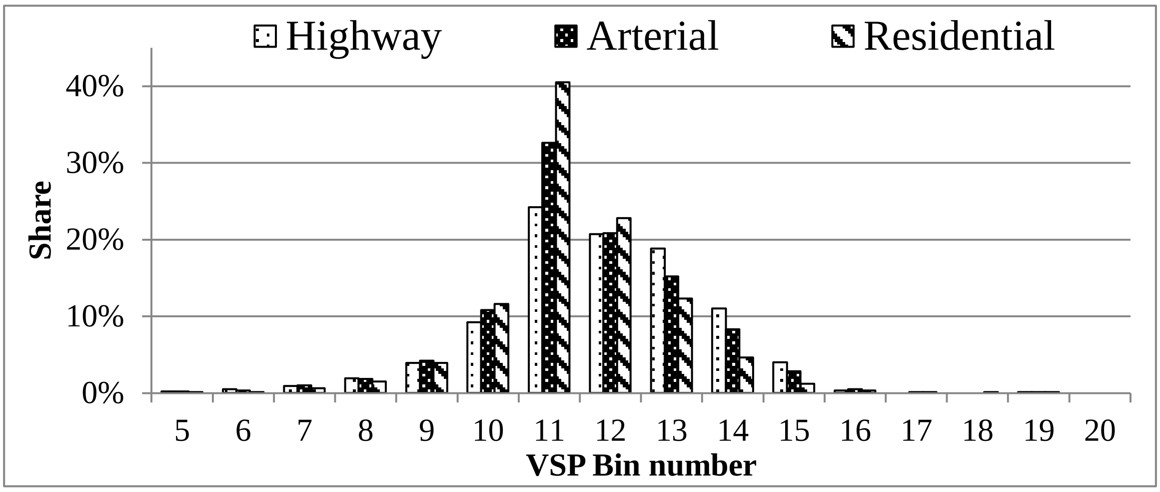

Fig. 4.12: VSP share for passenger cars on individual road types

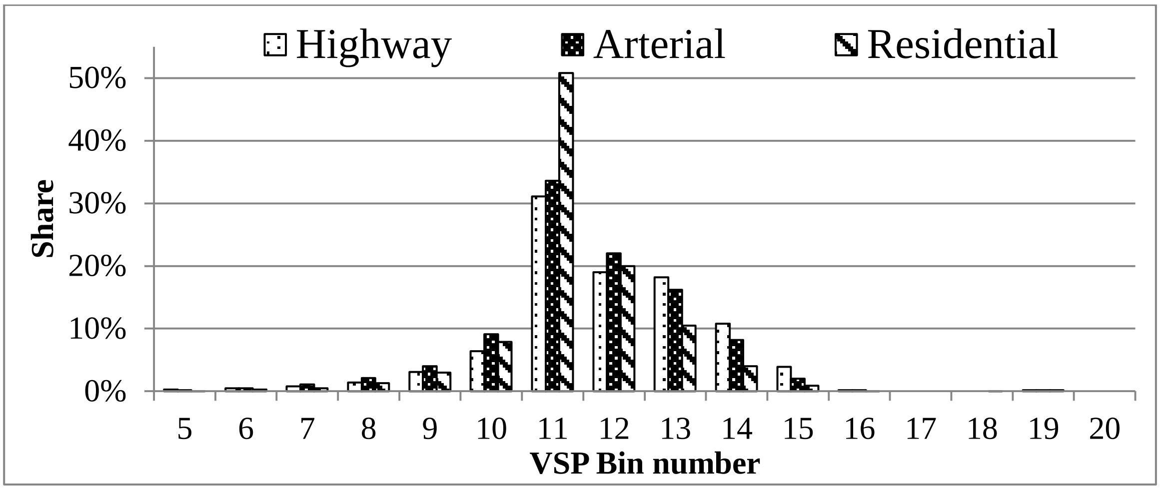

Fig. 4.13: VSP share for taxis on individual road types

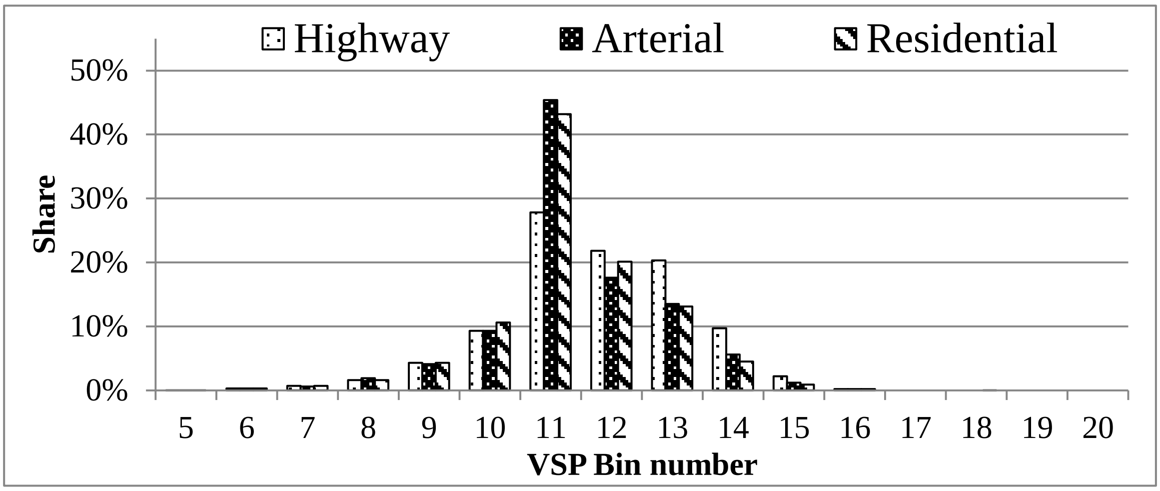

Fig. 4.14: VSP share for vans on individual road types

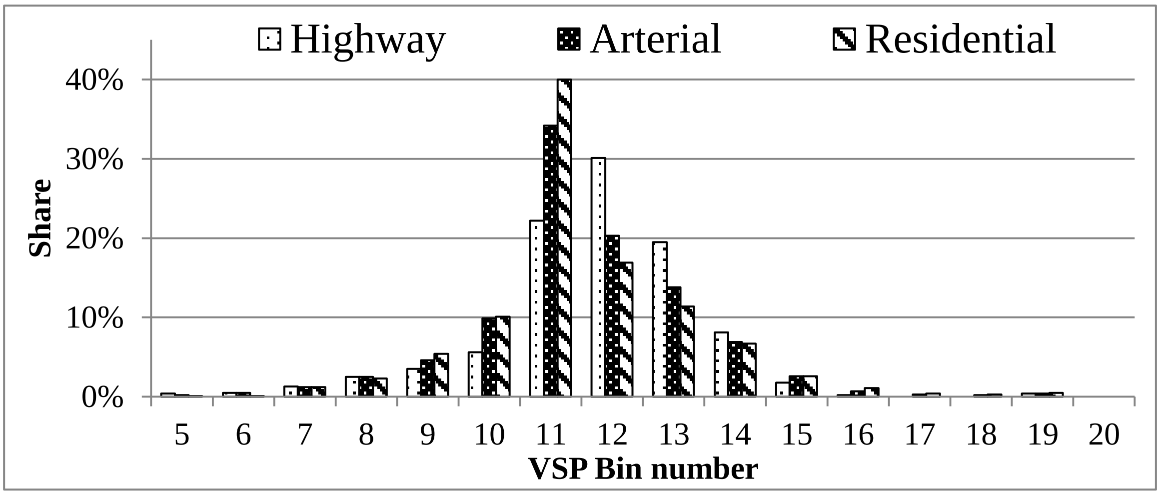

Fig. 4.15: VSP share for motorcycles on individual road types

4.5 IVE Model Based Emissions

4.5.1 Overall Daily Emissions in Islamabad City

Daily emissions estimates for the study period were obtained from running IVE model once the input files (fleet and location) were prepared and input into the model. Results reveal that daily emissions were highest for CO_2 at 2698 metric tons. This is a significant amount with a share of 84.8% in overall pollutant emissions from all types of vehicles considered in this study. As found in previous IVE studies and other studies, the transport sector is considered as one of the major sources of CO_2 emissions in most Asian countries (Timilsina and Shrestha, 2009). This was followed by CO (375 tons), total VOCs (47 tons), NOx (28 tons) and CH_4 (23 tons). Detailed daily emissions estimates are shown in Table 4.7 and Table 4.8. The share of major pollutants (namely CO_2, CO, NOx and PM) from vehicular emissions in Pakistan (Khan and Yasmin, 2014) is high along with significant amounts of VOCs and CH_4, benzene, formaldehyde & NH_3.

Table 4.7: Daily emission estimates for Islamabad

Pollutant	Start (Tons)	Running (Tons)	% Share (Start)	% Share (Running)
CO_2	83.95	2613.85	3.11	96.89
CO	70.68	304.47	18.84	81.16
VOC	9.87	37.43	20.86	79.14
NOx	4.95	23.26	17.55	82.45
CH_4	2.55	20.04	11.29	88.71
PM	0.33	0.58	36.65	63.35
SOx	0.02	0.53	4.39	95.61
NH_3	0.17	0.78	18.20	81.80
Benzene	0.56	3.21	14.93	85.07
N_2O	0.01	0.05	14.08	85.92
1,3 Butadiene	0.03	0.06	32.22	67.78
Acetaldehyde	0.11	0.22	34.01	65.99
Formaldehyde	0.43	0.81	34.59	65.41

4.5.2 Emissions by Technology Type

Each technology index used in the IVE model has a set of default EFs usually measured on U.S. vehicles and driving cycles. These default emission factors are normalized to local conditions by IVE model to produce local emission estimates thus their evaluation and analysis is necessary for better understanding of these emissions and their corresponding sources. Therefore, technologies types (with major share for each considered vehicle type) and their individual contribution towards total emissions was analyzed. IVE model results reveal that for all vehicle types, total emissions for major pollutants were not strictly dependent on their share in the fleet as shown in Figures 4.16 – 4.19. Detailed description of IVE technologies indices can be found in section 4.2.

This is due to the fact that some technologies produce lesser emissions even when their share is relatively high as can be seen for Index 180 (Euro II), and 198 (Euro IV) passenger cars. However, taxis showed a uniform reduction in emissions with decreasing share of a vehicles, with technology index 2 responsible for 65.3 per cent of overall pollutant emissions which is consistent with its population share of 62.8 per cent, whereas index 180 was responsible for 2.1 per cent (a bit lower than its population share of 3.1 per cent) of overall emissions from taxis in the city. Motorcycles, however, had a mixed emission pattern as their population share did not very significantly. For example, having few different characteristics, index 1211 motorcycle (engine: 100-300 cc, mileage>50,000 km, share: 6.8 per cent) produced 29 per cent more overall emissions as compared to index 1215 motorcycle (engine <100cc, mileage<25,000 km, share: 10.8 per cent) even with relatively smaller population share. This highlights the importance of individual technologies and their overall environmental impact regardless of their number.

The relative share of emission of pollutants with respect to four vehicle types was also analyzed and is presented in Fig. 4.20. Each pollutant had a varying share of sources.

Passenger cars had a higher share (>50 per cent) for CO_2, SOx and N_2O emissions. Taxis had the highest contribution in CH_4 emissions. Motorcycles had a share of more than 50 per cent for PM, 1-3 butadiene, acetaldehydes and formaldehydes emissions. For instance, motorcycles were found to be a major contributor to PM emissions and this can be attributed to older motorcycles in the fleet (Shen *et al.*, 2014). The PM emissions mainly coming from motorcycles should be reduced in order to avoid several health related problems (Pope *et al.*, 2009; Kim Oanh *et al.*, 2009).Emissions of NH_3 were coming from all vehicle types nearly proportional to their share in the vehicle fleet and VKT. However, these pollutant emissions require further consideration in order to better identify their improved emission control methods.

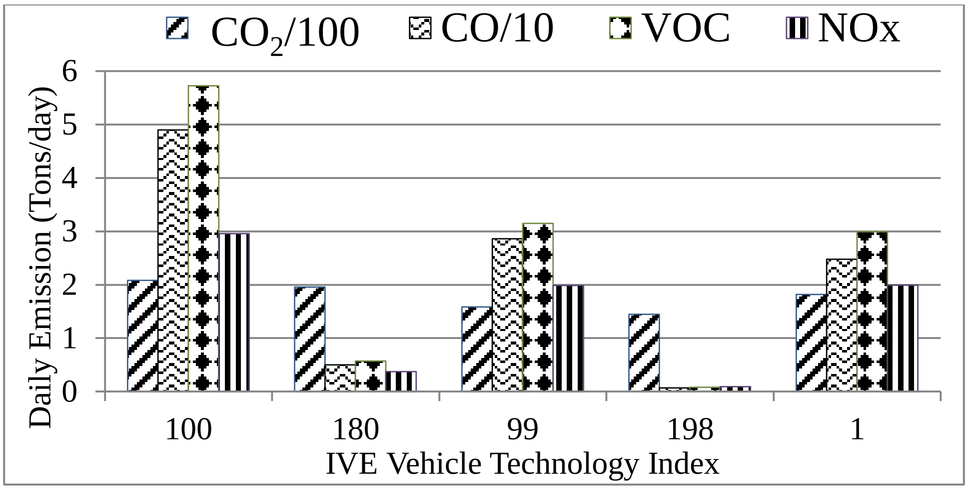

Fig. 4.16: Daily emissions for passenger cars based on IVE index vehicles

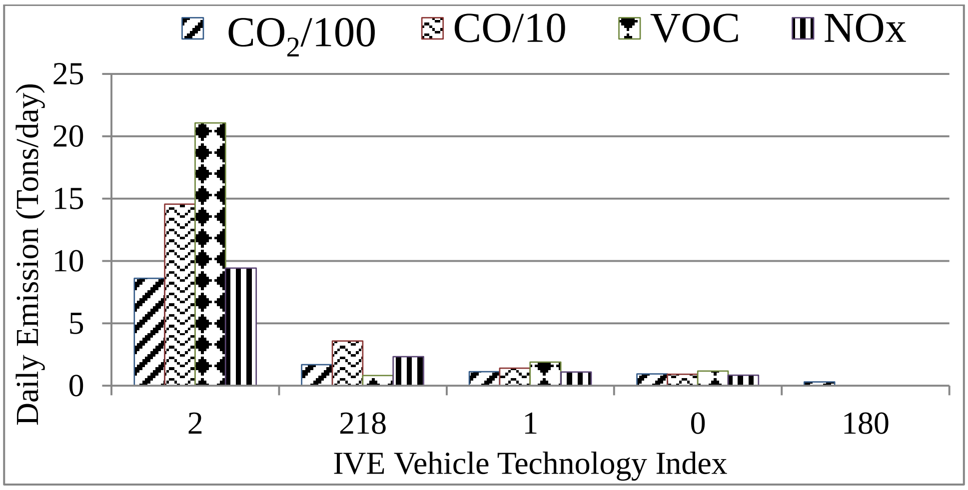

Fig. 4.17: Daily emissions for taxis based on IVE index vehicles

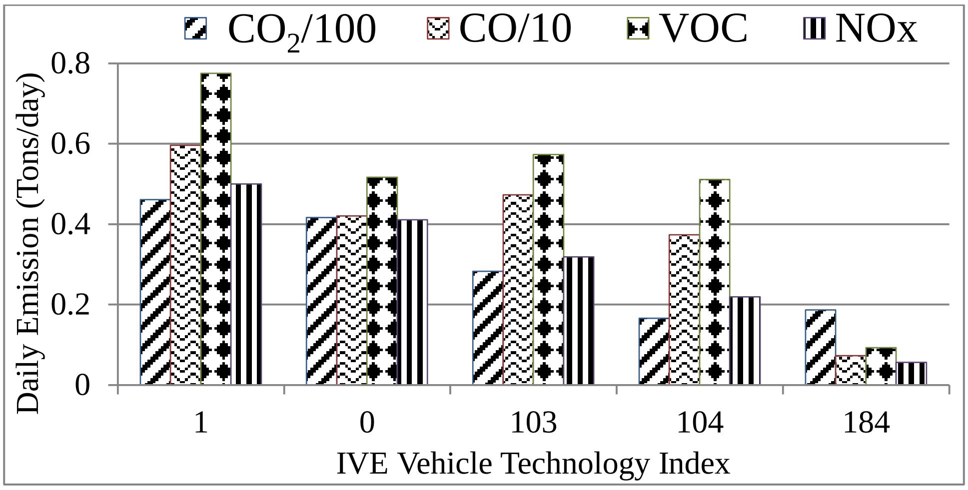

Fig. 4.18: Daily emissions for vans based on IVE index vehicles

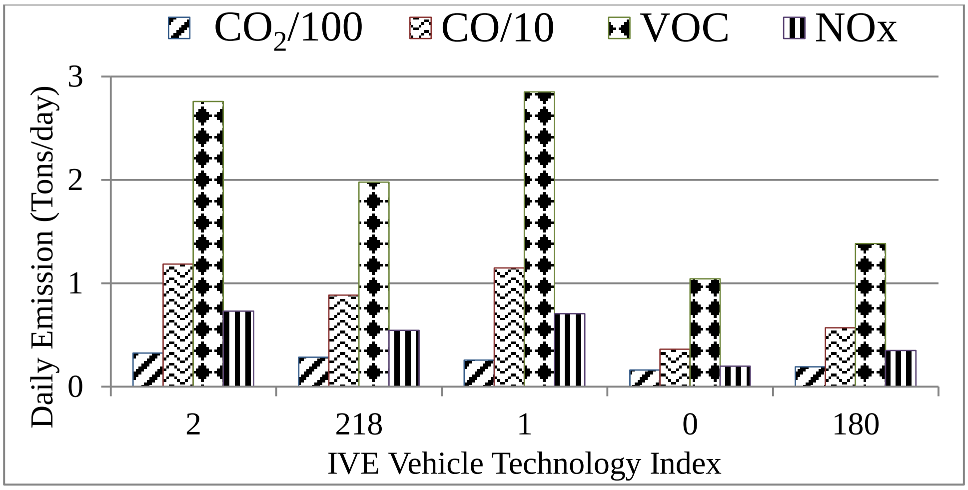

Fig. 4.19: Daily emissions for motorcycles based on IVE index vehicles

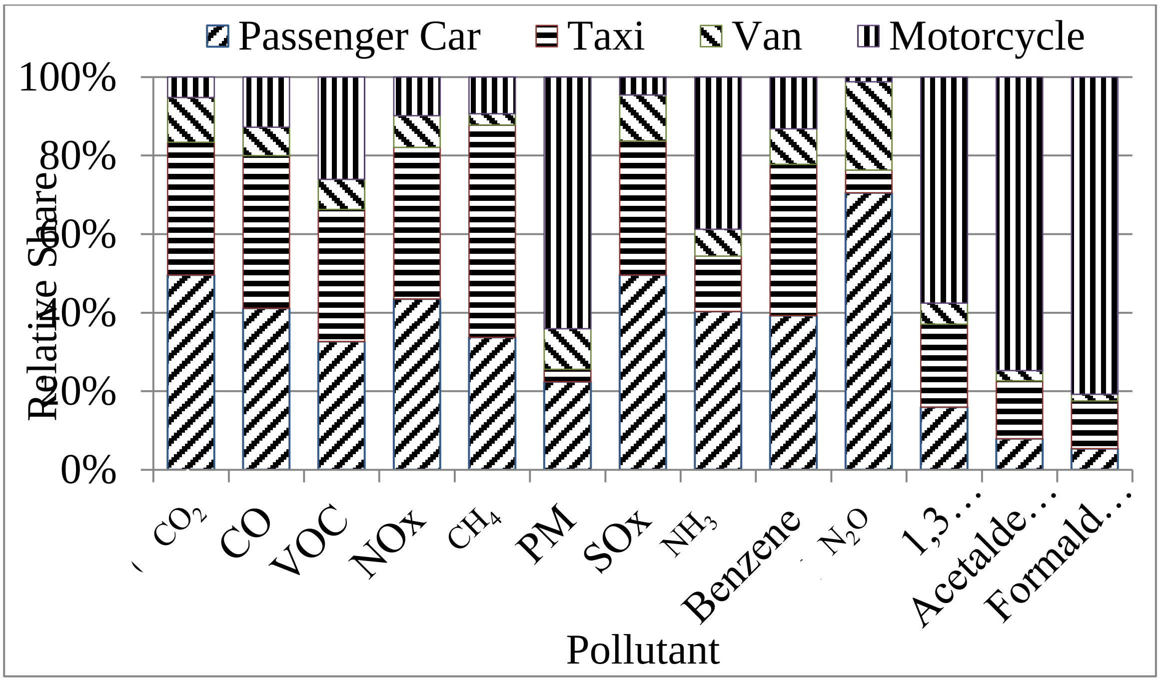

Fig. 4.20: Pollutant share for each vehicle type

4.5.3 Emissions by Road Type

Driving conditions vary with road type and with the time of day on a specific road type. Our results reveal that highways, arterials and residential roads were responsible for 17.6 per cent, 58.7 per cent and 23.7 per cent of overall emissions respectively. This can also be partly attributed to the shares of VKT on these road types as arterial had the largest share and highways had the smallest.

However, average speeds also have an impact on emissions as they were found to be minimum on residential roads and maximum on highways. Fig. 4.21 shows the share of each road type for all pollutants considered in this study. Passenger cars, taxis, vans and motorcycles were responsible for 48 per cent, 41.3 per cent, 4.4 per cent and 6.2 per cent of overall pollutant emissions on highways; 47.6 per cent, 33.9 per cent, 12.6 per cent and 6.5 per cent on arterials; and 49.6 per cent, 31.1 per cent, 10.7 per cent and 5.8 per cent on residential roads respectively.

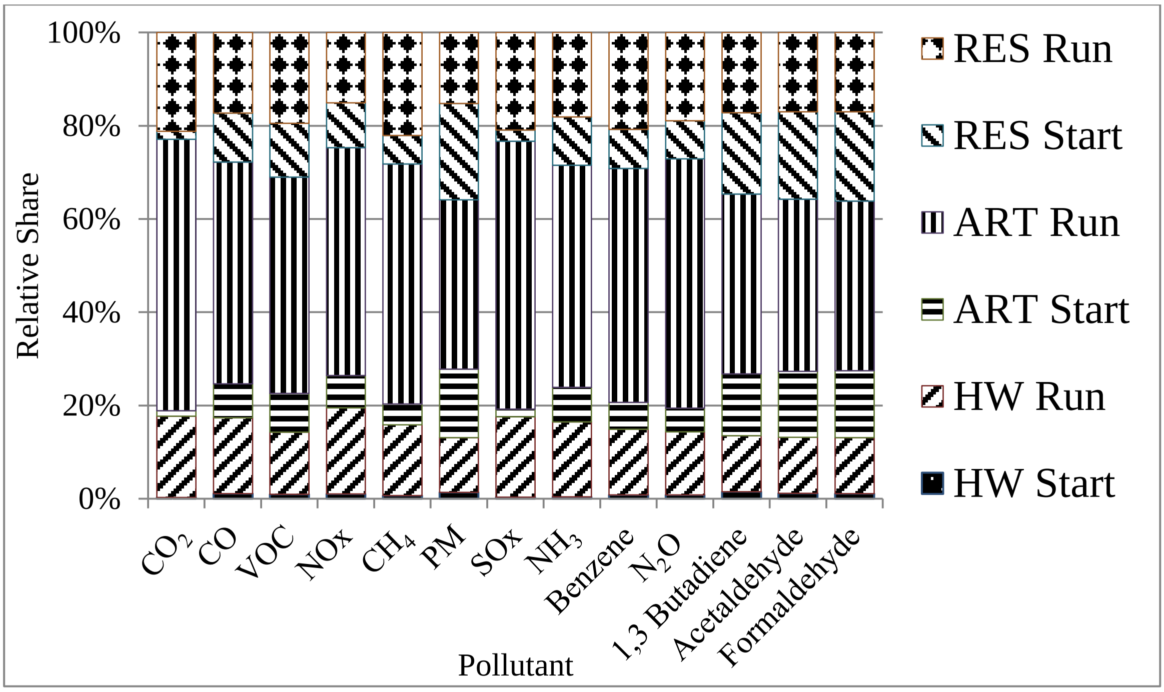

Fig. 4.21: Share of each road type in daily emissions (RES: residential roads, ART: arterials, HW: highways)

Higher overall emissions from taxis underline the fact that very old taxi fleet (average age of 20.36 years) together with its higher daily driving (119 km/day) is causing severe environmental damage even when it was found to be only 5 per cent of the on-road vehicle fleet. Emissions made by passenger cars are reflective of its large share (53.7 per cent) in the dynamic fleet of Islamabad. Motorcycles, however, were understandably responsible for only a small fraction of overall emissions on each road type notwithstanding their one-third share (32.1 per cent) in the on-road vehicle population.

4.5.4 Emissions by Time of the Day

Changes in driving conditions results in variation of overall emissions with respect to time. This change in emissions relative to time of the day for major pollutants is shown in Figures 4.22 – 4.25, while hourly variation in overall emissions is shown in Fig. 4.26.

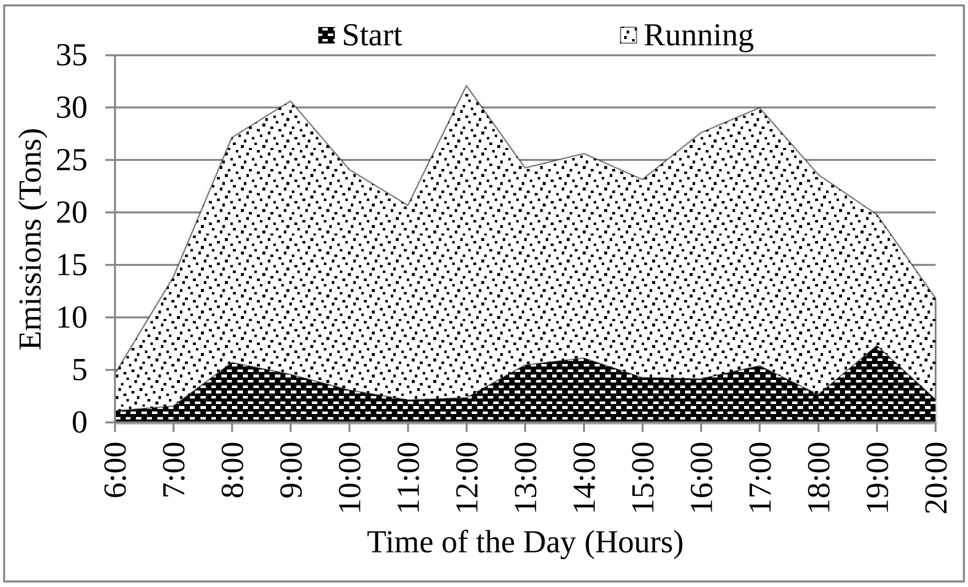

Fig. 4.22: CO emissions by hour (time: 0600 – 2000 hours)

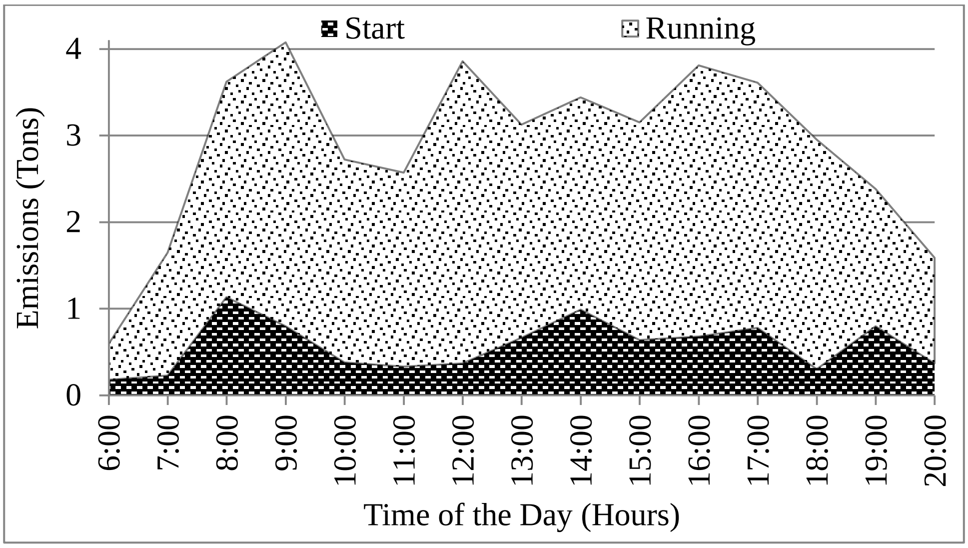

Fig. 4.23: VOCs emissions by hour (time: 0600 – 2000 hours)

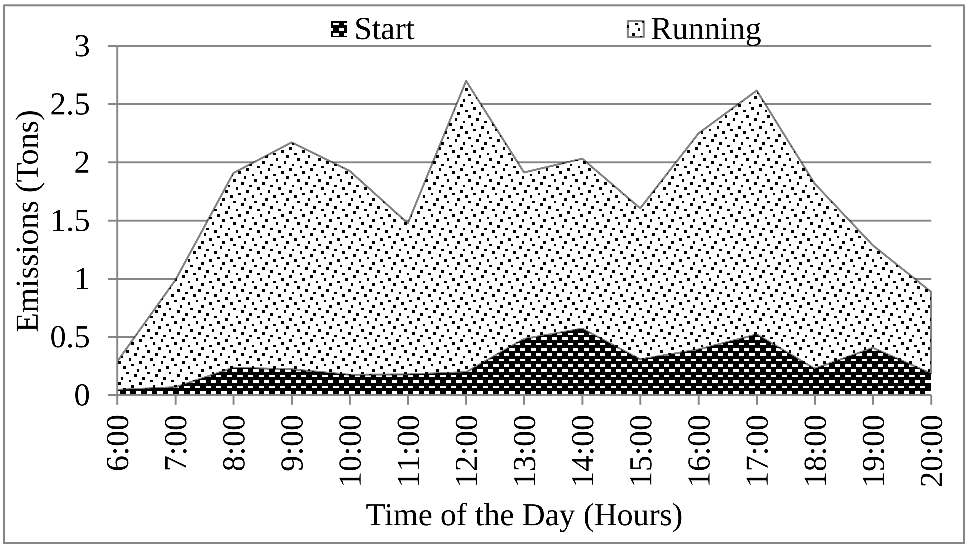

Fig. 4.24: NOx emissions by hour (time: 0600 – 2000 hours)

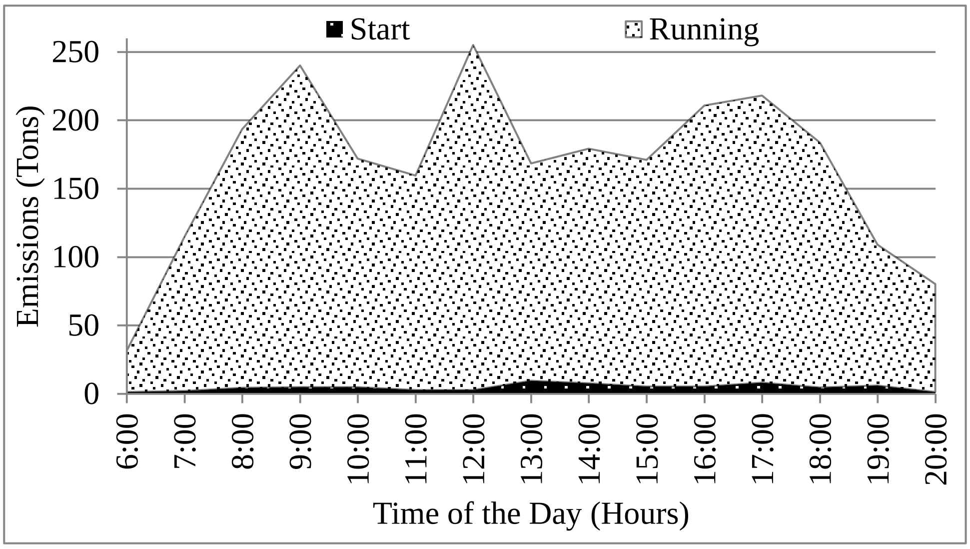

Fig. 4.25: CO_2 emissions by hour (time: 0600 – 2000 hours)

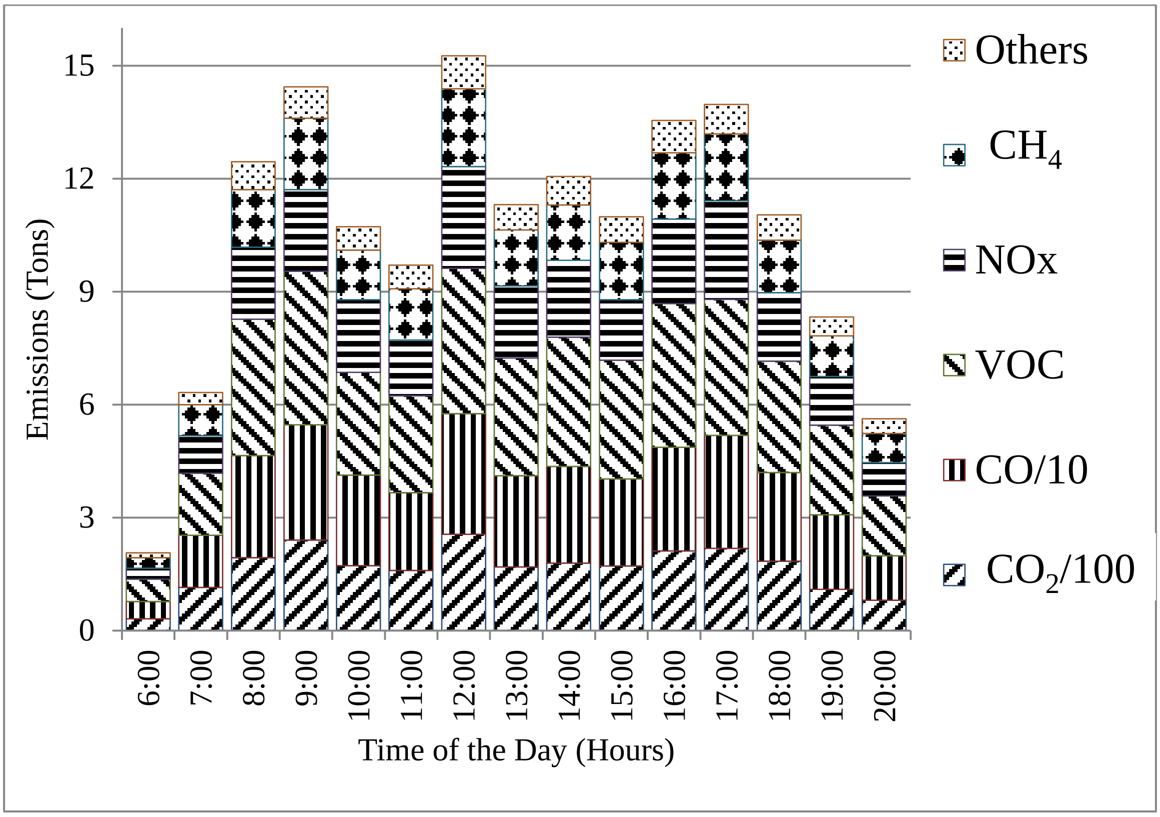

Fig. 4.26: Overall emissions by hour (Note: other include PM, formaldehyde, NH_3 benzene, SOx, N_2O, 1,3-butadiene and acetaldehyde)

4.6 Composite EFs & Annual Emissions

Emission of pollutants relative to the activity producing them is given by experimental values in terms of emission factors. These factors can forecast the amount of a pollutant that will be released relative to the distance travelled, fuel consumed, or energy utilized for operation and are affected by driving behaviors, ambient conditions, fuel characteristics, vehicle technology and emission control equipment (Franco *et al.*, 2013). Running composite EFs were determined by weighting average EFs for each road type against their share in total VKT while start composite EFs were weighted against share of each road in vehicle startups and the results are shown in Table 4.8.

Emission inventory, on the other hand, is considered to be an integral part of air pollution management (Mishra and Goyal, 2014) and was calculated for the year 2014 using the composite EFs, annual VKT and starts for every vehicle type considered in this study. Results showed that, 1093 kt of CO_2, 147 kt of CO, 18.5 kt of VOCs and 11 kt of NOx were emitted by LDVs during the year 2014; details are given in Table 4.8.

Table 4.8: Overall emissions and composite EFs (start and running) for Islamabad

Pollutant	**Overall Emissions (Tons)**		**Composite EFs**							
	Daily	Annual Inventory	Passenger Car		Taxi		Van		Motorcycle	
			g/start	g/km	g/start	g/km	g/start	g/km	g/start	g/km
CO	375.2	146,554	16.17	19.13	19.81	36.07	14.31	21.89	25.59	10.31
VOC	42.13	16,493	1.12	1.9	1.27	3.52	1.25	2.85	5.74	2.41
VOC evap.	5.17	1,965	0.2	0.12	0.80	0.43	0.22	0.2	1.41	0.23
NOx	28.22	11,136	0.98	1.63	1.5	2.69	1.11	1.84	2.24	0.41
SOx	0.56	226	0.01	0.04	0.01	0.05	0.01	0.06	0.001	0.01
PM	0.91	347	0.04	0.02	0.01	0.01	0.08	0.06	0.28	0.14
1,3 Butadiene	0.09	37	0.003	0.002	0.008	0.004	0.003	0.004	0.03	0.01
Acetaldehyde	0.33	129	0.01	0.003	0.02	0.01	0.01	0.01	0.12	0.06
Formaldehyde	1.24	470	0.012	0.006	0.063	0.032	0.02	0.02	0.48	0.25
NH_3	0.96	385	0.01	0.06	0.01	0.04	0.004	0.06	0.21	0.08
Benzene	3.77	1,482	0.12	0.2	0.13	0.37	0.123	0.29	0.27	0.11
CO_2	2698	1,093,613	25.08	206.8	32.9	236.32	25.4	294.2	6.86	52.54
N_2O	0.06	23	0.003	0.005	0.001	0.001	0.003	0.011	0.001	0.0
CH_4	22.59	8,810	0.503	1.049	1.085	3.09	0.23	0.55	1.15	0.48

Chapter 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusion

- Data for last 5 years showed an average addition of 62,000 vehicles each year to city's overall vehicle fleet.
- Passenger cars had the largest vehicle share followed by motorcycles, taxis and vans.
- Lower share of Euro compliant vehicles was observed for all vehicle types. However, due to import of vehicles from other countries, share of vehicles with Euro IV emission standards was reasonable for passenger cars and vans (17 per cent and 10 per cent, respectively) but negligible for taxis and motorcycles.
- Large vehicle population did not comply with Euro standards, therefore emissions were higher.
- Average vehicle ages were also higher (>6 years) for all types.
- Taxis were responsible for 35 per cent of overall emissions even with an on-road vehicle share of 5 per cent due to extremely high average age of 20.37 years and larger daily driving of 118.6 km.
- With respect to road types, arterials were responsible for 59 per cent of overall emissions while residential roads (lower speeds, higher EFs) and highways (higher speeds, lower EFs) had a share of 24 per cent and 17 per cent respectively.
- Higher emissions were observed during morning (8-10 am) and evening (4-6 pm) hours.
- Results showed that 1093 kt of CO_2, 147 kt of CO, 18.5 kt of VOCs and 11 kt of NOx were emitted during the year 2014 from light duty vehicles in Islamabad.

5.2 Recommendations

→ Research level suggestions for future work in this area include:

- Future studies undertaken to consider alternate fuels or vehicle technology scenarios that may have a positive impact on the air quality of the city.
- Improved driving conditions (higher average speed, high engine stress mode etc.) can be assumed to assess their potential impact on local emissions.
- Driving patterns can be recorded after the completion of the ongoing mass transit bus project in the city and results compared with this study.
- Buses and trucks can also be included in future to study their emission share.

→ Policy level interventions can be designed to reduce vehicular emissions such as:

- Effective vehicle Inspection & Maintenance (I/M) programs.
- Vehicle population control measures & volunteer removal of pre-Euro vehicles.
- Flexible and/or un-parallel working hours to avoid rush hour congestion.
- Improved public transit & traffic management in the city.

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