AIR QUALITY MODELING AND ITS LIAISON WITH TRANSPORT SUSTAINABILITY IN LAHORE PAKISTAN.

Rizwan Haider

Registration No.

2012-PhD-ENVS-42

Session 2012-2015

Sustainable Development Study Center

Government College University Lahore

AIR QUALITY MODELING AND ITS LIAISON WITH TRANSPORT SUSTAINABILITY IN LAHORE PAKISTAN.

Submitted to GC University Lahore

in partial fulfillment of award of the requirements

for the award of degree of

Doctor of Philosophy

in

Environmental Sciences

by

Rizwan Haider

Registration No.

2012-PhD-ENVS-42

Sustainable Development Study Center

Government College University Lahore

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Date: ______________

____
Supervisor
Dr. Engr. Abdullah Yasar
Director:
Sustainable Development Study Center
Government College University,
Lahore.

Submitted Through:

____
Dr. Engr. Abdullah Yasar
Director:
Sustainable Development Study Center
Government College University,
Lahore.

____
Controller of Examinations
Government College University,
Lahore.

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Certified that research work contained in this thesis titled "Air Quality Modeling and its liaison with Transport Sustainability in Lahore, Pakistan" was conducted by Mr. Rizwan Haider, Registration No. 2012-PhD-ENVS-42 under supervision of Dr. Engr. Abdullah Yasar.

It has been evaluated and the quantum and quality of the work contained in this thesis is found to be adequate for the award of degree of Doctor of Philosophy in Environmental Sciences.

Board of Examiners for Viva Voce	
External Examiner Name: Dr. Sajid Rashid Ahmad Designation and Office Address: Principal (Professor) of College of Earth and Environmental Sciences University of the Punjab Lahore	Signature
External Examiner Name: Dr Abdul Wahid Designation and Office Address: Chairperson (Professor) Department of Environmental Sciences. Bahauddin Zakariya University Multan	Signature
Internal Examiner (Superviser) Name: Dr. Engr. Abdullah Yasar Designation and Office Address: Sustainable Development Study Center Government College University, Lahore.	Signature
Convener Name: Dr. Engr. Abdullah Yasar Designation and Office Address: Sustainable Development Study Center Government College University, Lahore	Signature

ACKNOWLEDGEMENT

First of all, thanks to Almighty “ALLAH” who makes the mankind with lot of courage to know, discover and invent. And guide us through his books and Prophets. Thanks to the HOLY PROPHET “MUHAMMAD” (S.A.W.) who guide us to withstand against all evils and to improve life style of humanity through innovations, research, policies, hard work, mercy, equality, team work and sacrifice. And enables us to recognize our creator and provide us the knowledge that each other power in the world is the creation of Almighty Allah.

Thankfully, by the grace of Almighty Allah, I had support of a number of people who provided assistance and encouragement in the completion of this research project, which was not less than a daunting task for me.

I deem it as my utmost pleasure to avail this opportunity to express deep sense of obligation to my highly learned supervisor Dr Engr. Abdullah Yasar, whose illustrious advice, intellectual stimulation, encouraging attitude, invaluable suggestions and inspiring attitude which made it very easy for me to undertake this work throughout the course of this research work. During this research, I came to know so many technical points about air pollutants, meteorology, vehicular emission factors, air pollution models, statistical techniques, transport sustainability etc.

I also wish to express my gratitude to lab staff of the centre & all Members of **Research Progress Review Committee,** organized by the Chairperson of the department. Committee’s incredible guidance, sustained encouragement, constructive criticism and sympathetic attitude during the period of my research enabled me to technically tackle all the problems during the course of study. As an ex expert of air quality monitoring station of Environmental Protection Agency Lahore and as ex Incharge of vehicular pollution control section, the many aspects of the study were properly performed. Special thanks to the GCU laboratory for provision of portable instruments of air quality and meteorological parameters.

RIZWAN HAIDER

Abstract

The current research work is an effort to cover different aspects of urban and transport related air pollution. Urban air quality monitoring and vehicular exhaust emissions monitoring are relatively new topics for a developing country like Pakistan. Euro II emission standards for vehicular exhaust emissions have been opted as Pak II in the country, since 2009. The fuel quality is substandard than Euro II standards. Emission factors or any local urban driving cycle for different classes of vehicles has not yet been established by any of the Provincial or Federal EPA. The transport system and the land use developments have very low transport sustainability. Public transport infrastructure is of conventional quality, forcing people to use their own transportation for their trips. The air quality monitoring through sophisticated instruments at different sites like, hotspots, roads, industrial area and rural areas, is a very expensive task for a developing country like Pakistan. Therefore, modeling is a useful technique to assess air pollutants level at different spots, especially road sides and in big cities like Lahore, Pakistan.

An attempt has been made to find out diurnal & monthly mean pattern of air pollutants, their interrelationship and their dominant sources through hourly and monthly data analysis. Horiba air quality monitoring instruments have been used to monitor hourly, monthly, seasonal air quality and meteorological data of Lahore. Lahore is a semi-arid region with low rain-fall, hot & humid summers and cold dry winters. Annually, highest Air Quality Index (AQI) (132 to 185) has been observed from November to February due to inversion at low wind speed (< 1.5 m/s monthly average), low temperature (15°C to 21°C monthly average) and low solar radiations (104 to 140 W m^{-2} monthly averages). AQI remained low (74 to 85) from June to August due to relatively heavy rain, relatively high wind speed (1.59 to 1.85 monthly averages), dispersion as a result of high temperature (30°C to 32°C monthly average), high solar radiations (211 to 236 W m^{-2} monthly averages) and summer vacations to schools. With an analogous diurnal trend, the AQI remains low at day-time. High ratio of CO/NOx indicates that mobile sources are dominant contributor to CO; and low ratio of SO_2/NOx indicates that point sources are dominant contributor to SO_2. CO has a significant positive correlation with NO, NO_2, NOx, CH_4, SO_2 and RH. While CO has negative correlation with O_3 and temperature. The positive correlation of CO with NO, NO_2, NOx, CH_4 and SO_2 explains 4-stroke petrol engines as a common source for these pollutants. $PM_{2.5}$ has a significant positive correlation with

SO_2; which explains diesel engines as a common source for $PM_{2.5}$ and SO_2. O_3 has a significant negative correlation with NO, NO_2, NOx, CH_4, CO and relative humidity. While a significant positive correlation has been observed among O_3, temperature and solar radiations.

Transport sustainability is a novel topic for public and policy makers in the country. Many efforts have been performed by the provincial Government to control traffic congestions through introduction of overhead bridges, under passes and u-turn bridges in the city. A ring road has also been introduced to link different parts of the city. A 27 Km long metro bus has been introduced on Ferozepur road and 31 Km long metro orange line train project is under construction. CNG buses have been promoted in the city. But most of the the land use development policies do not take transport sustainability into account. This research is intended to find out sustainable transport indicators and transport sustainability index for the five roads of Lahore, Pakistan. The main indicators of transport sustainability are taken as shifting of modes from private to public vehicles, land use planning and sustainable operations. In a way thirty-five transport sustainability indicators have been selected. The opinion of stake holders has been taken by a questionnaire by randomly interviewing around four hundred citizens. The social survey pointed out that distance from bus stop, time taken and length of journey (≥ 4 out of 5 grades) are important factors in preventing people from using public transport. Time, convenience, safety, reliability, relaxation and health (≥ 4 out of 5 grades) remained important factors in the choice of public transport. Cheaper fares, availability of school/work bus, more reliable service, more bus routes and extended bus service (≥ 4 out of 5 grades) were considered as important factors to promote public transport. None of the advertisement technique was ranked above 4 to promote public transport during the survey. Transport sustainability index of Ferozepur road, Gulberg main boulevard road, Jail road, Mall road and Multan road were 47.14, 38.57, 40, 34.29 and 34.29 respectively.

Another main task of the research is to find out emission factor of different classes of vehicles to model the certain air pollutants level in five different main streets. Motorcycles constitute more than 50 % of the vehicular traffic on most of the roads. The percentage of cars varies from 26% at Multan road to 37% at Jail road. The background urban emissions data has been monitored through air quality monitoring station installed at Town Hall building at Mall road. The air pollutants level has been modeled with the help of Operational Street Pollution Model (OSPM). The data of

street configuration, background urban air pollution, meteorological conditions, diurnal traffic count and emission factor of vehicles has been monitored to model the pollutants level at different streets. A significant correlation (r-value > 0.5) has been observed between modeled and observed results for all the streets for NOx, SO_2 and CO levels, except for NOx level at Gulberg (r-value= 0.42). The better modeling results have been observed for those streets which are in relatively polluted spots and are close to the background urban air quality monitoring station.

Overall the air quality index of the Lahore city remains high in winter season due to meteorological conditions. The $PM_{2.5}$ level remains much higher than NEQS throughout the year especially in winter season. Petrol engines are the main source of CO and diesel engines are the main source of SO_2 emissions in the city. O_3 levels remained high in summer season during a calendar year and at day time during a day. The transport sustainability index is very low (< 50) for all five selected roads. People were found reluctant to use public transport due to factors like much time consumption, inconvenience and distance from bus stop. There is need to introduce many innovations in land-use development and public life style to promote transport sustainability in the city. The signal free tracks have improved the speed of vehicles at many roads in the city. It has been calculated that with 10% decrease of cars and 10 Km/hr gain in speed (from 40 to 50 Km/hr) can reduce the CO and benzene emission factor of cars by 33.2% and 25.7% respectively. Each vehicle in the city has much high emission factor as compared to modern vehicles, due to substandard fuel quality and relatively old engine types in the city. A significant correlation has been found among observed and modeled results on five selected roads of Lahore. And modeling technique has been found to show significantly acceptable results of street air quality modeling, on different roads of Lahore.

Abbreviations

AQI:	Air Quality Index
ATM:	Active Traffic Management
CFD:	Computational Fluid Dynamics
CNG:	Compressed Natural Gas
CO:	Carbon Monoxide
EIA:	Environmental Impact Assessment
EPA:	Environmental Protection Agency
HC:	Hydrocarbon
ITS:	Intelligent Transport System
JICA:	Japan International Cooperation Agency
LPG:	Light Petroleum Gas
NASA:	National Aeronautics and Space Administration
NEQS:	National Environmental Quality Standards
NMHC:	Non-Methane Hydrocarbon
NO:	Nitrogen Oxide
NO2:	Nitrogen Dioxide
NOx:	Oxides of Nitrogen
OMI:	Ozone Monitoring Instrument
OSPM:	Operational Street Pollution Model
PM:	Particulate Matter
RH:	Relative Humidity
SEUS:	Semi-Empirical Urban Street Model
SO_2:	Sulfur Dioxide
SPSS:	Statistical Package for the Social Sciences
SUPARCO:	Pakistan Space and Upper Atmosphere Research Commission
STI:	Sustainable Transport Indicator
T:	Temperature
TDM:	Travel Demand Management
THC:	Total Hydrocarbons
TSI:	Transport Sustainability Index
TSP:	Total Suspended Particulate Matter
VOCs:	Volatile Organic Compounds
WS:	Wind Speed

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INTRODUCTION

CHAPTER 1

1. Introduction

This chapter explains the need and inspiration of this research work. Different environmental aspects of urban air pollution, transport related air pollution, transport sustainability and transport related air pollution modeling have been introduced in this chapter. The objectives and usefulness of the research have also been explained in this chapter.

1.1. Urban air quality of Lahore

Population of Lahore is 11.12 million, making it second largest city of Pakistan (Pakistan Bureau of Statistics, 2017). The annual growth rate of population is 4.07 since 1998 (Pakistan Bureau of Statistics, 2017). There are around 4.28 million vehicles along with 1986 different industrial units in Lahore (Punjab Bureau of Statistics, 2016). The ambient air pollution in the city predominantly originates from vehicular and industrial emissions (Stone et al., 2010) . The semi-arid climate of Lahore, naturally favors the accumulation of pollutants. Solid aerosols are present in the samples of PM (Shahid et al., 2013). New housing schemes have not been found to fulfill the needs of sustainable development goals and transport sustainability. City District Government has been failed to achieve its target of ambient air quality improvements under the devolution plan 2001 due to absence of transport policy, alteration in land use policy, deprived management and monitoring of air quality (Aziz et al., 2013) . Further the city has been expanding due to migration from small cities of Punjab. Migration has been observed from Karachi and Peshawar as well, due to security reasons. People from all over Punjab province; visit Lahore for business reasons, interviews, medical facilities and also to protest to achieve certain goals.

Diesel-fueled generators have been used extensively in industrial sectors (point sources) as well as in other sectors due to widespread power shortage in the country, which adds a lot to urban ambient air pollution (IMF, 2010). Use of diesel fuel by the mobile sources contributes a lot to particulate matter air pollution (Assistance et al., 2001). The sulfur contents are very high in diesel (0.5-1%) and furnace oil (1-3.5%) available in Pakistan, which fallout in high sulfur dioxide pollution (Purohit et al., 2013). The environmental damages are associated with health issues. Currently the mobile sources have been found to promote high levels of tropospheric ozone and health concerns in urban areas (Wang et al., 2011).The Organosulfatese have been recognized and measured in fine particulate matter ($PM_{2.5}$) collected in Lahore, Pakistan, during 2007–2008 (Bilenko et al., 2015). The enhanced diastolic blood pressure has been found to be related with long-standing exposure to NO_2 and $PM_{2.5}$ in those children who used to live at the same place since birth (Kundu et al., 2013).The $PM_{2.5}$ levels have been exceeding the NEQS in four provincial as well as federal capital of Pakistan (Rasheed et al., 2015). In the fall season during October and November; burning of crop residues in a region eastern Pakistan and northwestern India, surge the concentration of $PM_{2.5}$ in atmosphere (Singh and Kaskaoutis, 2014; Tariq et al., 2014). Secondary inorganic PM in the form of sulfates and nitrates is formed by the oxidation of SO_2 and NOx. However, organic carbon fraction is formed due to oxidation of VOCs (Jacob and Winner, 2009; McMurry et al. 2004; Zhang et al., 2008). This process is enhanced by ammonia by forming ammonium nitrate and ammonium sulphate as solid particles (Aneja et al., 2009). The black carbon aerosols are present 90% in the form of $PM_{2.5}$ in winter season and contributes about 5-15% to overall $PM_{2.5}$ in the ambient air (Husain et al., 2007; Viidanoja et al., 2002). The black carbon has been found to be at much higher level during foggy season. The black carbon has also been found to be trapped in aerosols during foggy season, resulting in lessening of solar radiations (Das et al., 2015).

Other big cities in province Punjab have also high level of air pollutants. Concentration of CO, NO_2 and SO_2 has been found to exceed NEQS level in Faisalabad (Niaz et al., 2015). The traffic pollution has been found to be the most contributing factor to outdoor air pollution in most of the urban areas (Basarić et al., 2014). Brick kilns, on the boundaries of the Lahore city are also a great point source of air pollution. A study on brick kilns in Wahga and Batapur areas of Lahore revealed that the conventional Bull's Trench Brick Kiln are being used in Lahore, which comprises no control measures to manage the air pollution. The modern brick manufacturing technologies such as vertical shaft brick kiln must be introduced to control the air pollution (Guttikunda, 2014).

In a recent study on some metals in the vehicular exhaust emissions of rickshaws, it has been discovered that a significant boost has been found in Al, P and Zn in the PM samples of four stroke Rickshaws (Anwar et al., 2013). In a recent study on different metal concentration level in Lahore, mean levels of iron, lead, nickel and zinc remained very high i.e. 23.08 µg/m^3, 6.23 µg/m^3, 7.95 µg/m^3 and 15.36 µg/m^3 respectively; while copper, chromium, manganese and arsenic levels remained low in ambient air. (Jalees and Asim, 2016). In another study in Beijing, China, perfluorinated compounds (PFCs) were found in ambient $PM_{2.5}$, PM_{10} and TSP samples (C. Zhang et al., 2016).

A careful review of the existing studies suggests that available studies only cover the level of air pollutants in Lahore. Studies coping critical analysis, correlation & ratio analysis or application of any model or prediction system for urban emissions, are not available for the Lahore city. More over indicators of transport sustainability and transport sustainability index (TSI) has not been proposed for Lahore in previous studies. The research has focused on to assess different aspects of vehicular air pollution in Lahore e.g. contribution of vehicular pollution to ambient air, modeling of vehicular pollution level at street level, transport sustainability, and association between transport sustainability and street/ road air quality.

1.2. Lahore and its meteorology

Climate of Lahore can be distributed into five seasons:

Foggy winter (15 Nov- 15 Feb) with low rain-fall, low wind speed and high inversion; spring (16 Feb – 15 April) with low rain-fall and moderate temperature (T); summer (15 April – June) with high temperature, high rain-fall, low relative humidity (RH) and high dispersion effects; rainy monsoon (July – 16 September) with high temperature, high relative humidity and low pollution due to dispersion and washing effect and dry autumn (16 September –14 November) with low wind speed and low RH (Wikipedia, 2015). June is the hottest month with an average temperature around 33.9 °C. The average temperature of January is 12.8 °C, which makes it the coolest month of the year. The average annual temperature of Lahore is 24.3 °C, which is fairly hot as annual average. Average monthly temperature range is 21.1 °C. The average daily temperature variation is 15.5 °C (Wikipedia, 2015).

The minimum average sunshine has been observed in January with 6.9 hours day^{-1}. Overall annual average sunshine is 8.4 hours day^{-1} (Wikipedia, 2015). The wind speed remains low almost throughout the year except some windy days in summer. Around 60 % days of the year remains calm (wind speed < 0.5 m/sec) and 33% of the days have average speed of 1-3 knots. Only 6% days of the year express speed of 4-6 knots. Wind direction remains mostly north-west during monsoon and summer and south-east during winter season (Wikipedia, 2015). Relative Humidity (RH) remains low throughout the year except during monsoon season. Monthly average of relative humidity remains above 60% during July, August and September. Average relative humidity remains around 77% in the morning and 40% in the evening. The average monthly RH ranges around 20% in May to 58% in August. Overall the annual average relative humidity remains around 37.9%. The climate of Lahore has observed extreme weather events in the near past. The highest ever recorded temperature of the city was 48.3 °C on 30 May, 1944 and 48 °C on 10 June, 2007. The highest recorded rainfall was 221 mm observed on 13 August, 2008. Highest hailing (4.5 mm) was observed on 26 February 2011 (Wikipedia, 2015).

1.3. Different aspects of the study

1.3.1. Scope of air quality monitoring

In, 2007, Environmental Protection Agency, Islamabad Pakistan installed fixed air quality monitoring stations in Islamabad and Provincial capitals with the technical and financial coordination of Japan International Coordination Agency (JICA). Lahore city was equipped with two fixed and a mobile air quality monitoring station. Although these monitoring stations are not sufficient to monitor the air quality of big city like Lahore; but still provide a way forward towards the air quality monitoring of the Lahore city, and formation of National Environmental Quality Standards (NEQS). The fixed air quality monitoring station installed at the Town Hall building at Mall road has been chosen as urban background ambient air emissions monitor in the current study.

There are two fixed air quality monitoring stations in Lahore. One of the stations has been installed, in busy commercial area at Town Hall Building at Mall road. The second station has been installed in a residential area namely Township, near Kotlakhpat industrial estate. The air quality monitoring station at township shows relatively high levels of SO_2 and low levels of CO emissions due to nearby industrial estate. Therefore, air quality monitoring station at Town Hall building has been taken for data analysis of Lahore, as a semi-arid region.

To assess the dominant source of different pollutants, ratio and correlation studies of the measured pollutants have been performed. Hourly data of air quality monitoring, for the years (2007-2011 and 2014-2015) from air quality monitoring station in Lahore has been analyzed as background data for ratio & correlation studies of six major pollutants. Air quality has been monitored at different spots, like rural side, urban background, industrial area, road side and hotspots. This study contributes to an organized evaluation of urban pollution conditions in Lahore and points out the sources that affect air quality. This study has assessed the dominant source of air pollutants; either they are from transport sector or from industrial sources.

1.3.2. State of air quality in Lahore

The economic development at a rapid rate in the developing world, have strong correlation with elevated urban air pollution. The same phase of industrialization and motorization has been on the way in Pakistan. The WHO has reported that two third of the deaths were due to urban air pollution in developing nations of Asia. The 24-hour average of $PM_{2.5}$ has been found to be much higher than set standard of 35 µg/ m3. According to the data provided by monitoring in Lahore, Rawalpindi, Karachi and Peshawar, the $PM_{2.5}$ and PM_{10} concentration has been found to be almost 6 times higher than WHO guidelines (Majid et al., 2012). Moreover low ratio of $PM_{2.5}$ to PM_{10} points out high content of coarse dust particles in the air, leading to reduced visibility (Majid et al., 2012). The high levels of $PM_{2.5}$ mainly emit from exhaust emissions of automobiles, generators and industrial stacks. The level of ambient air pollution remains very high on main roads of Lahore throughout the year due to traffic load. The urban population of Lahore has been increasing at very high rate of 3% per annum (JICA, 2012). The migration has been observed from small cities to Lahore due to availability of educational, medical and employment facilities in Lahore. The migration from suburban areas to Lahore has created huge travel demand. The inner zone of the Lahore is highly populated. The population density varies from 100 persons per hectare to 450 persons per hectare from outer to inner zone of Lahore respectively. It has been estimated that around 80 % of the population has been living in a radius of 7-8 Km in the center of the city (JICA, 2012). Living in such populous area, makes it substantial to be exposed to urban air emissions. Particularly, many research results pointed out that public health has been harmed to a considerable level by vehicular emissions especially by fine particulate matter like PM2.5 and PM10 (Colvile et al., 2002; Mediavilla-Sahagún and ApSimon, 2006; Park et al., 2006; Oxley et al., 2009; Holnicki et al., 2010; Buchholz et al., 2013).

The private vehicle ownership has been increasing at the rate of 17 % annually (JICA, 2012). Heavy traffic load has been observed on main roads of Lahore. Government has taken number of steps to reduce the congestions on different roads. Number of roads have been made signal free through construction of underpasses, overhead bridges and roundabouts. Similarly, new roads have been made to reduce load on existing roads. A clear reduction in congestions has been observed at different hot spots due to smooth flow of traffic through underpasses and overhead bridges. Most of the citizens use private mode of transport due to inefficient public transport. The increase in number of cars has been observed to a great extent in recent years due to bank leasing, groomed lifestyle and decrease in usage cost. The increased number of cars are one of the main factor of congestions and reduced safety for motorized and non-motorized mode users (Esmael et al., 2013).

1.3.3. Sustainable transportation

United nations have introduced 17 sustainable development initiatives for sustainable and peaceful world for mankind by 2030 (United Nations 2015). The goal 11 deals with sustainability of cities. The target 11.2 states that:

"By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons" (De Gruyter et al., 2016).

Better transportation is essential part of modern life as it provides ease to perform different human activities. Transportation has a key role in all three key areas of sustainable development: environmental, social and economic goals, but also has long term impacts on environment, society and economic growth (Santos and Ribeiro, 2013). There is a need to adopt steady policies of transit sustainability. Toronto and Edmonton, despite of their low population and high ownership rate have improved their riding habits. A good transport system always improves the ridership habits (Vuchic, 2005). But, when the cities get bigger, only the mass transit systems can control the emission levels, as certain enforcements for cars might not be fruitful to control emission levels, as in case of Beijing and London (Kelly and Zhu, 2016). According to Excise & Taxation department Lahore, there were around 4.28 million registered vehicles in Lahore on 30th June, 2015 (Punjab Bureau of Statistics, 2016). Congestions have been observed on hotspots during peak hours. The AQI (air quality index) always remains above 100 on main roads especially in winters. The noxious air pollution has been becoming cause of number of avoidable deaths (McGranahan and Murray, 2012).

The main purpose of recent European Transport Policy documents is to meet the economic, social and environmental goals of the society (Palensky and Dietrich, 2011). The European commission have suggested lighter & efficient vehicles with advanced combustion engines, reduction in road transport, promotion of GHGs legislations, adoption of electric & hydrogen fuel vehicles, social & economic measures, planning and certain measures to reduce transport demand, for a climate friendly transport system, by 2030 (Luè, et al., 2016). Overall planning, comprehensive land use planning surveys, transport studies and traffic senses are required for future needs and for adequacy of individual projects (Bhatti, 1994). Agricultural land has been decreasing at great speed due to horizon of new housing societies in Lahore. Additional agricultural land will be required as a result of crop losses due to decrease in agricultural lands, increase in new diseases & pests, environmental pollution and climate change(Cicekli and Barlas, 2014).

With the introduction of underpasses, overhead bridges, parking facilities, foot paths, road lights, different kinds of signals, roundabouts and above all the metro bus system; Lahore has become a potential city to achieve better sustainable transport. Sustainable transportation suggests a parallel model that assumes each mode of transportation to be equally important. An ideal system for sustainable transportation would be a balanced transportation structure that incorporate each mode significantly (Litman and Burwell, 2006). The walk is considered most sustainable mode , then bicycle, train, bus, automobile and improved automobiles are taken in sustainability order, respectively (Ardekani and Bakhtiari, 2012)

A more sustainable transport system always has a better air quality. The study includes following aspects of transport,

i. Facilities for pedestrians;
ii. Promotion of bicycle;
iii. Promotion of public transport like train, bus etc
iv. And many other aspects like availability of signals, roundabouts, sustainable lights, parking areas, parks etc

1.3.4. Transportation and three dimensions of sustainability

The sustainable cities may have certain urban environments, which are not simply overload by personal cars; instead walk, cycling routes and systems for public transport are promoted in a sustainable city (Cheshmehzangi and Thomas 2016). The indicators of sustainable transportation have been described in number of studies as statistical data that indicates the sustainability of environmental, social and economic developments (Haghshenas and Vaziri, 2012; Joumard and Nicolas, 2010). Kennedy established that it is obvious for some cities to have an adequate governance structure to mature sustainable urban transportation systems with better emphasis on mobility and accessibility (Kennedy et al., 2005). For a sustainable transport system, the transportation must be safe & accessible and environmentally sound to help improve the health social equity and the resilience of the citizens (Santos and Ribeiro, 2013). According to Hens and De Wit, lengthy lists of indicators have been established to explain the complexity of sustainable development (Hens and De Wit, 2003). However recent lists have been minimized to core indicators of environment, social and economic indicators. Many of the researchers conclude the need of more research (Toth-Szabo et al., 2011). Depending on the specific context, function of sustainable transport indicators (STI) may vary with different priorities. In many world cities, sustainability indicators have been applied to monitor the progress of transportation (Mori and Christodoulou, 2012).

Indicators can be useful to describe the growing need of particular sustainability at local or regional level and to compare the situation with other territories.(Mascarenhas et al., 2010). Policy makers take into account the economic, social and environmental impacts to their synchronized evolution (Mihyeon Jeon and Amekudzi, 2005; Litman, 2009; Litman, 2010; Toth-Szabo et al., 2011). An index that only consider economic impacts, can formulate decisions which can be harmful environmentally; and an index which taken into account only environmental impacts, can impose decisions which are economically not favorable (Litman, 2009).

1.3.5. Air pollution modeling of different roads/streets

Another main aspect of the study is to assess the air pollution level at different streets with the help of models. The emission factors of different classes of vehicles are set with the help of OSPM, by providing data like fuel quality, engine type and average speed of vehicles. For this purpose, Operational Street Pollution Model (OSPM) is used to model the vehicular exhaust emissions as contributor to air pollution in different streets of Lahore. The OSPM model has been widely used to model air pollution for European cities. The OSPM has also been successfully used to model NOx emissions in Chembur (industrialized and congested area with automobiles, near Mumbai India) (Kumar et al., 2016). The OSPM is operational and relevant dispersion model for assessment of street air quality. The modeled results are compared with observed results through graphs and correlation analysis.

The OSPM model used in the current study calculates the traffic produced turbulence. The OSPM software requires street configuration (street width, street orientation and building height), meteorological data and background urban emissions data to model the air pollution of vehicles. The vehicles average speed and defined emission factors are necessary to model the pollution level in certain streets.

1.3.6. Air pollution modeling soft-wares

Air quality modeling soft-wares has an important role in management and prediction of urban emissions, which are crucial for urban air emissions management (Gulia et al., 2015). There is always an uncertainty in modeling results especially in urban areas (Holnicki and Nahorski, 2015). But still modeling technique is quite useful to assess air pollution levels. The Operational Street Pollution Model (OSPM) has been used to model the air pollution at five busy roads of Lahore. The OSPM model is a street canyon pollution dispersion model, which has been widely used to model air pollution. The basic data required for OSPM comprises of flow conditions of different automobiles in streets, street configuration and metrological conditions (Hertel and Berkowicz, 1989; Berkowicz et al., 1997). A combination of plume and box model is used to model the dispersion and transport of pollutants. Currently, OSPM has been widely used to calculate traffic pollution and pollution trends in European streets (Assael et al., 2008). The Gaussian plume model measures the direct contribution from the automobiles and the box model is used for the mixed ambient air pollution, circulating in the street due to presence of hurdles around the street (Berkowicz et al., 1997). The OSPM model has been successfully used in Stockholm, Helsinky, Copenhagon, China, USA, Vietnam and India (Fu et al., 2000; Ziv et al., 2002; Aquilina and Micallef, 2004; Mensink et al., 2006; Vardoulakis et al., 2007; Berkowicz et al., 2008; Jensen et al., 2009; Hung 2010; Kumar et al., 2016).

1.4. Objectives

The available studies regarding air pollution in Lahore lack critical analysis. Most of the studies just show the levels of different pollutants. Correlation studies are required to analyse negative or positive correlation between different pollutants. Studies regarding extent of pollutants contribution to ambient air by different sources are also required. And most importantly, studies of air pollution modeling at street and urban levels are vital for the city of Lahore.

The main purpose of the current research is to calculate and model the traffic related air pollution. More over the study is extended to analyse the state of ambient air quality in Lahore Pakistan. The analysis of the study also includes the discovery of the dominant sources of air pollution and interdependence & correlation of air pollutants with meteorological parameters. Therefore, following are the objectives of this research work.

1. The first objective involves the monitoring and statistical analysis of urban air quality. The task involves compilation of air quality data from fixed air quality monitoring stations in Lahore (which has already been monitored from 2007-2011) and monitoring of urban air quality from 2014-2015. Ratio analysis of CO/NOx and SO_2/NOx, to point out the dominant sources of certain pollutants at certain locations. To find out correlation and interdependence of air pollutants and meteorological parameters with each other.
2. To find out air quality at different sites like rural area, urban background, road side, hotspots and industrial area. And to discuss the reasons of level of different pollutants at different sites.
3. To sort and select indicators of transport sustainability according to local resources and requirements. In a way to set a transport sustainability index for different streets according to extent of compliance to selected indicators. To conduct a social survey to take the opinion of citizens about their mode of transportation, hurdles in the use of public transport, initiatives to take to promote public transport, important factors in the use of public transport and importance of different tools to aware the public to promote public transport.
4. To find out diurnal traffic pattern in the selected streets/roads. To calculate emission factor of different classes of vehicles with the help of OSPM software depending upon fuel quality, engine type, mode of transportation and

average speed. To determine the street configuration like street orientation, building height and street width.

5. Modeling of air quality in different street with OSPM by providing back ground urban emissions data, street configuration, diurnal vehicular data, average speed, emission factors of vehicles and meteorological data. To calculate correlation between observed and modeled results to determine the efficiency of modeling technique and input data.
6. To find out liaison of air quality with selected transport sustainability indicators through determination of improvement in air quality with introduction of certain sustainable measures in the city.

REVIEW OF LITERATURE

CHAPTER 2

2. Review of Literature

2.1. Conceptual framework

Air quality monitoring is a subject of much attention and importance throughout the world. Number of air quality monitoring stations and metrological stations have been installed throughout the world to consistently monitor the air quality and meteorological conditions throughout the globe. Urban air quality and its health concerns are challenge for both scientists and policy makers. Sustainable measures in different sectors like land-use planning, shifting of modes and different operations can minimize the urban pollutants level. The modeling techniques in different sectors can make the monitoring of air quality very easy and economical.

2.1.1. Air quality

Back in eighteenth century, the study of atmospheric chemistry was adopted as a discipline to study the major gases like nitrogen, oxygen, water vapors, carbon dioxide and noble gases. Later on attention turned towards trace gases (less than 1 ppm and even upto 1 ppb) like NOx, CO, SO_2, O_3 and CH_4 (Seinfeld and Pandis, 2016). Therefore, major portion of the troposphere comprises of nitrogen and oxygen gases. Carbon dioxide, methane and some noble gases are present in small amount in the atmosphere. The health hazard gases like oxides of nitrogen (NO, NO2 & NOx) and sulfur (SO_2, SO_3), ozone (O_3), hydrocarbons (HC, CH_4, NMHC, THC), hydrogen sulfide (H_2S) and respirable particulate matter ($PM_{2.5}$, PM_{10}) are dangerous for health even at parts per billion (ppb) levels or microgram per cubic meter (µg/m3) levels. Carbon monoxide is dangerous at parts per million (ppm) level or milligram per cubic meter (mg/m^3) level. The pollutants like NOx, SOx, CO, HCs and $PM_{2.5}$ are produced mostly from burning of fossil fuels by mobile, point, line sources etc. O_3 is produced as secondary pollutant from burning of fossil fuels in the presence of sunlight. Air pollution has become a serious health hazard for urban areas. The matter of air quality management is becoming serious for big cities now. The air quality management strategies have taken hold since last decade of twentieth century (Griffin, 2016).

2.1.2. Categorization of air pollution sources

Air pollution sources are usually categorized into four classes, namely point, line, volume and area sources:

- Industrial stacks are usually considered as point sources. Further evaluation of the point sources involves volume of emission, stack diameter, stack height etc.
- Vehicles on certain street or road are considered as line or mobile sources. Line source is taken as a one-dimensional source of air pollution.
- A certain urban area or colony is considered as an area source. The area source represents the emissions from domestic or household sources. The area source is considered as two-dimensional cause of air pollution.
- The three-dimensional sources are taken as volume sources. An open lime stone mine is an example of volume source (Milton R.Beychok, 2006).

There are different kinds of sources of air pollution in Lahore e.g. industries, household, vehicular etc. Different chemical analyses are involved among air pollutants in the presence of different metrological conditions and many other factors. Different studies have suggested that few monitoring stations may not express the difference in pollution levels at different parts of the city. The developing countries may not be able to afford the lavish cost of the number of air quality monitoring stations. Therefore, air quality models become much important to model the air quality in various sectors of the city with the help of urban background air quality monitoring station data.

As an urbanized country of South Asia, Pakistan has population of 207.77 million (Pakistan Bureau of Statistics, 2017). Like many developing countries, air pollution is on the rise as an impact of rapid economic growth due to industrialization, in Pakistan. Industrial activities, vehicular exhaust emissions, and coal fired power plants are among the main contributor to air pollution in the country (Rasheed et al., 2014). Numbers of diesel generators are being used in the country due to power shortage. These diesel generators are contributing a lot to urban air pollution in the country (IMF, 2010). The dependence of transport sector on diesel as fuel is another source of particulate matter emissions in the country (Shyamsundar et al., 2001). The quality of fuel is very poor in the country, especially the level of sulfur is very high in furnace oil (1-3.5%) and diesel (0.5-1%) as compared to international Euro standards

(Martin et al., 2006). An annual loss of about Rs. 365 billion has been observed due to environmental damages, of which the urban air pollution cost is approximately Rs. 65 billion (Colbeck et al., 2010). The level of particulate matter is reported to be at peak in Karachi (668 µg/m3), among 18 mega cities of the world (Gurjar et al., 2008). The population of big cities has been increasing to a great extent; especially Lahore has expanded to an immense level in recent few years. The population of Lahore has been increased to an estimated level of 10 Million in 2006 (Jason et al., 2009). In 2008, Lahore was ranked as a city with potential to turn into a gamma city (Rasheed et al., 2015).· Lahore has been ranked as the 2nd largest city of Pakistan, 5th largest city of south Asia and 23rd largest city on the globe (Rasheed et al., 2015). Biswas has reported the average $PM_{2.5}$ levels to be many times greater in Lahore than Seoul, New York City and Hong Kong (Raja et al., 2010). The concentration of NOx and PM_{10} has been reported to be higher than WHO standards in Lahore, in a joint venture study by Pak-EPA and JICA in 2000 (Pak-EPA and JICA, 2000).

2.2. Current scenario

The world population has been increasing at a rapid rate. The increase in world population has been mostly from the developing and under developed nations. One of the main features of the developing nations is emerging urbanization. According to united nations estimates, more than 90% of the urbanization has been observed in developing nations (Habitat, 2006). The migration to big cities due to lack of facilities at grass root level and in small cities, has created all sorts of problems, like dense population, traffic congestions, air pollution, slum conditions, health issues etc, in big cities of developing countries, like Lahore. Under developed countries are in a phase of economic development at a considerable rate. The rapid urbanization often results in enhanced ambient air pollution levels. In the coming 20 years, the urban population will be 2 billion in the developing countries, with a rate of 70 million per year. The urban population will be doubled in Asia and Africa at that time. Around 80% of the urban population of the world will be living in developing countries, by 2030 (Hung, 2010).

Pakistan is one of those developing countries, which has been going through industrialization period with considerable increase in motorization and energy use. The population and area of big cities of Pakistan has been increasing at considerable rate. Lahore is the second largest city of Pakistan. In recent few years a certain boom in population and car usage has been observed in Lahore. The vehicles are the main source of air pollution in the urban areas and cause certain health impacts on road users and urban communities. Emerging population as well as improvement in living standards demands more and more vehicles, energy usage, food supplies, more personal cars and imported items. The enhanced use of air conditioners, fridges and other electronic equipment's demands more electric supply for the city. Lahore city depends on neighboring cities for its food and milk supplies. Many citizens travel to Lahore for Jobs, interviews, tests, education and healthcare matters. Many main markets like that of steel, electronics, domestic items, agricultural goods, cars etc are situated in Lahore, which results as a traffic burdon on Lahore city. The number of vehicles has been increasing in province Punjab and Lahore at a considerable rate. A trend of increase of total number of vehicles, cars, motorcycles and auto rickshaws from 2006 onward in Lahore, has been given in Fig. 2.1.

In 2007, two fixed air quality monitoring station were installed in Lahore by Japan International Cooperation Agency, in coordination with Federal EPA Islamabad. The location of the monitoring stations has been shown in Fig. 3.3. A mobile air quality monitoring station was also provided to monitor certain areas of province Punjab.

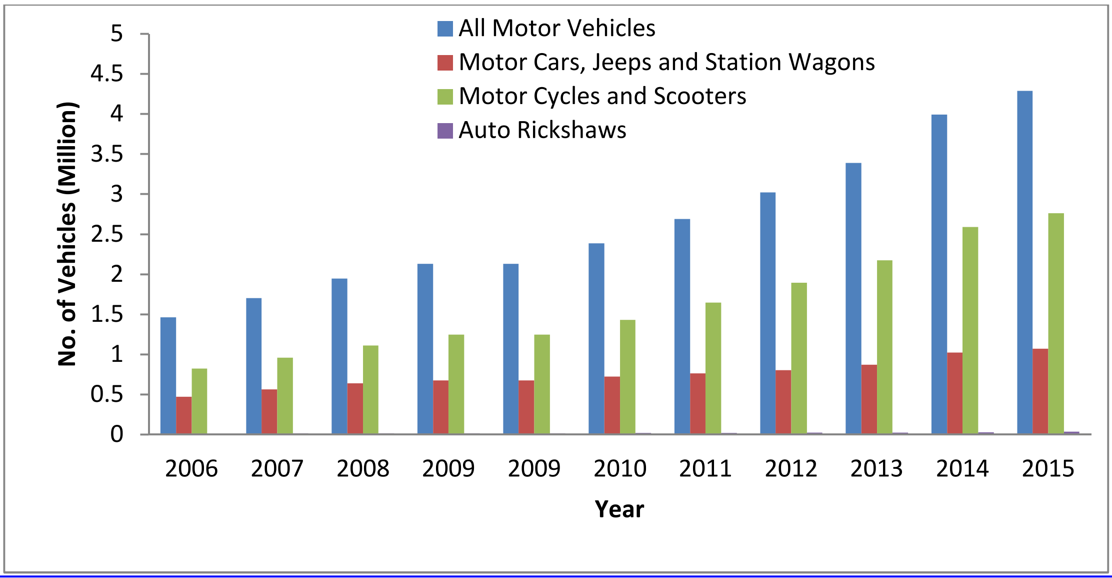

Fig. 2.1. Trend in increase of vehicles in Lahore

The overall rate of increase of total number of vehicles, cars and motorcycles remained 14.97%, 9.73% and 18.18% respectively in province Punjab from 2005 onward 2014. While in Lahore, average rate of increase remained 12.7 %, 9.6 % and

14.5 % for all motor vehicles, cars and motorcycles respectively from 2006 to 2015, as shown in Table 2.1. The significant increase has been observed in number of motorcycles due to its low buying and operational cost. Total number of registered vehicles has crossed figure of 5 million in 2016 in Lahore.

Table 2.1. Rate of increase in vehicles in Lahore

Years		All Motor Vehicles	Motor Cars, Jeeps and Station Wagons	Motor Cycles and Scooters	Trucks	Delivery Vans	Buses	Taxis	Auto Rickshaws	Tractor	Other Vehicles
2006	No.	1464344.0	473311.0	822264.0	11439.0	33243.0	27792.0	10586.0	58024.0	26540.0	1145.0
2007	No.	1703007.0	561500.0	957939.0	14146.0	37036.0	31365.0	11660.0	59627.0	28415.0	1319.0
	Rate of increase (%)	16.3	18.6	16.5	23.7	11.4	12.9	10.2	2.8	7.1	15.2
2008	No.	1944709.0	637787.0	1110218.0	15999.0	40133.0	32518.0	11771.0	66246.0	28575.0	1462.0
	Rate of increase (%)	14.2	13.6	15.9	13.1	8.4	3.7	1.0	11.1	0.6	10.8
2009	No.	2129990.0	673449.0	1245389.0	17029.0	42315.0	33335.0	11771.0	74259.0	30757.0	1686.0
	Rate of increase (%)	9.5	5.6	12.2	6.4	5.4	2.5	0.0	12.1	7.6	15.3
2010	No.	2387993.0	722012.0	1432639.0	18683.0	45094.0	34132.0	11789.0	87541.0	34220.0	1883.0
	Rate of increase (%)	12.1	7.2	15.0	9.7	6.6	2.4	0.2	17.9	11.3	11.7
2011	No.	2687987.0	764265.0	1647842.0	20806.0	48046.0	35345.0	11867.0	102029.0	37305.0	20482.0
	Rate of increase (%)	12.6	5.9	15.0	11.4	6.6	3.6	0.7	16.6	9.0	987.7
2012	No.	3022126.0	801403.0	1894324.0	22772.0	78621.0	36841.0	14766.0	113007.0	39551.0	20841.0
	Rate of increase (%)	12.4	4.9	15.0	9.5	63.6	4.2	24.4	10.8	6.0	1.8
2013	No.	3391268.0	871244.0	2172760.0	24683.0	81922.0	40485.0	15146.0	222517.0	42191.0	20320.0
	Rate of increase (%)	12.2	8.7	14.7	8.4	4.2	9.9	2.6	96.9	6.7	-2.5
2014	No.	3991517.0	1023110.0	2588254.0	27344.0	86753.0	43972.0	15247.0	139927.0	45971.0	20939.0
	Rate of increase (%)	17.7	17.4	19.1	10.8	5.9	8.6	0.7	-37.1	9.0	3.1
2015	No.	4287662.0	1070243.0	2763872.0	36265.0	130344.0	50519.0	17404.0	149562.0	47356.0	22097.0
	Rate of increase (%)	7.4	4.6	6.8	32.6	50.3	14.9	14.2	6.9	3.0	5.5
Average rate of increase (%)		12.7	9.6	14.5	14.0	18.0	7.0	6.0	15.3	6.7	116.5
Vehicles registered during 2016		1694580	1694580.0	120577.0	1458603.0	-	-	-	-	-	-

Source: - Additional Director General, Excise & Taxation, Punjab, Lahore.

A trend of increase in number of vehicles has been observed in Lahore. A total number of 4287662 vehicles were registered in Lahore, in 2015; of which 64.2% were motorcycles and 25% were cars, jeeps and station wagons, as shown in Fig. 2.2.

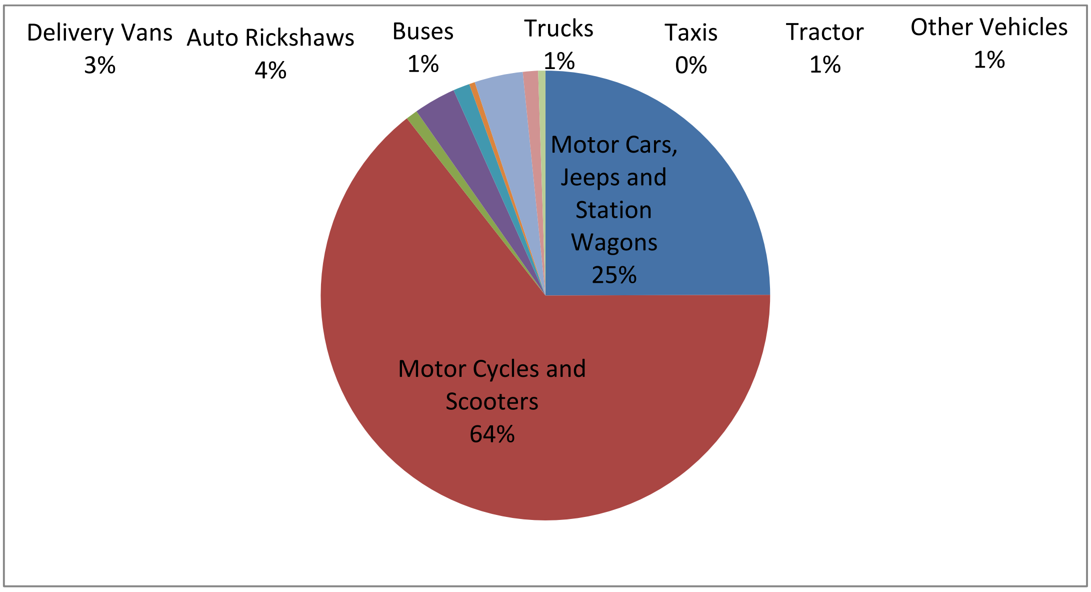

Fig. 2.2. Percentage of registered vehicles in Lahore

2.3. Transport sector of Lahore

Transportation has facilitated the modern life style in many ways. There are social, economic and environmental imbalances related to modern transportation system. The world's vehicle fleet has been increasing due to population growth, urbanization and economic improvement. Population of the Lahore city has been increased at a very fast rate in recent few years. Reliance of number of other cities of Punjab and Pakistan on Lahore has led to increased population as well as vehicles. Pakistan is predominantly relying on road transport system for intercity as well as intra city transportation. The road transport has been increased at a much greater rate in Lahore than other cities of Punjab Province in the last ten years (Mirza et al., 2013). Number of overhead bridges and under passes has been established as a consequence to make roads signal free. Metro Bus project has been developed to provide better public transport to the public. The orange line train project is under construction to facilitate people. It has been found that higher share of tendering and small & long contracts makes the projects more efficient (Link, 2016). This factor of higher tendering has been claimed by the Government in case of orange-line metro train and metro bus projects.

The economy of the country essentially depends on better transportation system. But excessive and emerging noise and air pollution have become serious concern for the Lahore, city. Visible smog has been observed in the month of November in 2016 and 2017 in Lahore and many other cities of province Punjab. A holistic approach is required for sustainable growth of the city and to sustainably manage the transport of the city.

2.3.1. Travel demand management

Travel demand management is an effective tool to influence travel behavior, and to reduce travel cost and time, and facilitate travel options (Gärling et al., 2002). Travel demand management incorporates policies that improves the advantage of car usage and enhances merits of public transport (Gärling and Schuitema, 2007). Push (disincentive) and pull (incentive) measures are used in TDM. The push measures are to discourage the car use through fuel and road tax etc., and pull measures provide alternative choices like improved public transport, HOVs lanes (high occupancy vehicle lanes), van pooling etc (Steg and Vlek, 1997). TDM measures may also be classified as hard and soft measures. Hard measures include parking charges, road pricing, new public transport service etc. Soft measures include work place travel planning, personalized travel plans, travel awareness campaigns, marketing of public transport etc (Gärling and Fujii, 2009). European commission have proposed introduction of lighter & efficient vehicles with advanced combustion engines, reduction in road transport, encouragement of GHGs legislations, shift towards electric & hydrogen fuel vehicles and social & economic measures to reduce transport demand (Luè, et al., 2016).

2.3.2. Use of modern technologies in develop world

The develop world has adopted modern technologies like intelligent transport system (ITS) and active traffic management system (ATM). Many countries takes it as a high level objective to make highways environmentally & socially sustainable and economically sound to support low energy carbon future (Kolosz et al., 2013). Intelligent Transport System (ITS) is used to elaborate a combination of technology, information, communication, automation and positioning (Psaraki et al., 2012). The ITS aims to maximize the capacity of highways by generating enhanced performance within the network so as to avoid the additional need to construct highways (Deakin et al., 2009). The term sustainability has been used widely to describe social, environmental and economic concerns, even though there is uncertainty in its proper orientation (Hilty et al., 2006; Matthews et al., 2007). ATM gives a “smarter highways” concept by introducing different systems working together to improve traffic flow and to reduce road congestion. The ATM system is based on feedback data surveillance system which facilitate human operators to conduct necessity changes to highway signs to control the traffic flow. ATM also supports the performance of expected road network in different future scenarios like lane closure, increase in demand, special event etc. Through ATM, it is possible to adopt, test and improve future strategies.

ATM has been adopted by different countries worldwide. By 2005, the road network operator’s budget was £3 billion in UK, forcing the Transport Department to take conventional steps of road widening. In 2006, a successful trial of ATM in Birmingham was experienced over 16.4 Km area. By 2008, the road traffic has been grown 84 percent since 1980, by an increase of 318 billion vehicles miles from 172 billion miles. This has made this type of scheme essential. By 2010, the Washington State Department of Transportation of USA has first time enforced ATM schemes, with implementation of heavy fine for over speeding in the Seattle Metropolitan Area. (Kolosz et al., 2013). The primary ATM technologies were junction control, lane-specific signaling, temporary shoulder running, queue protection and ramp metering. In Germany, the traffic management strategies are based on queue warning, speed harmonization, temporary shoulder use, truck restrictions, junction control, dynamic rerouting, ramp metering, truck distance tolling and traveler information (Mirshahi et al., 2007). On the other hand Dubai with its all luxuries, has been ranked at lowest number (26th) in transport sustainability index survey of twenty six main cities of Middle East and Asia due to non sustainable policies (De Gruyter et al., 2016). It has also been observed that congestion charging and low emission zones in the city could not control excessive NOx in London; and in Beijing certain hurdles on control and purchase of vehicles could not control emission levels. As the cities get too big only mass transit system can control the emissions (Kelly and Zhu, 2016).

2.4. Air pollution modeling

2.4.1. Air quality models

Air pollution modeling is mathematical calculation or simulation, how air pollutants disperse in the air. The models are chosen to illustrate the chemical and physical procedures to set a level of pollution at different locations (Vardoulakis et al., 2003). The models are used to model the pollution level from point source, line source, mobile source etc. Five general types of models are used to predict or estimate the pollution level from different sources. The box model assumes that air pollutants have been homogeneously distributed in a box. The model has limitations due to homogeneous assumption of dispersion of pollutants. AURORA and CPB are examples of box model. Aurora is used to calculate the level of reactive gases and particles in urban areas (Mensink et al., 2006). CPB model is used to model air pollution of urban environment (Holmes and Morawska, 2006).

The Gaussian model is based on assumption that air emissions dispersion follows a Gaussian distribution. The Gaussian model is mostly used for continuous emission plumes produced from ground or from an elevated source. Gaussian models can also calculate vehicular emission dispersion. Gaussian model can be useful for non continuous air emission plumes as well. OSPM, CALINE4, UBM, AERMOD, and UK-ADMS models are some examples of Gaussian models. Gaussian models are not fit for complex systems, and for only shorter distances. Constant wind direction and wind speed is assumed in Gaussian models, which limits them to be used for shorter areas (Holmes and Morawska, 2006). Lagrangian models use mathematical calculations. Lagrangian model consider plume in the form of different parcels moving as a random walk. The dispersion of air pollution is calculated by statistical study of large number of plumes. This model is useful to calculate the pollutants dispersion over long distances. SPRAY model is an example of Lagrangian model (Holmes and Morawska, 2006). Eulerian model is designed like Lagrangian model to estimate the dispersion of air pollutants for lengthy distances. Large number of pollution plumes are used in Eulerian models as well. But a fix three-dimensional (Cartesian) grid is used as a frame of reference in Eulerian model. In Lagrangian model, a moving frame of reference is used. ALGRID model, ARIA Regional model, and the Danish Eulerian Hemispheric Model (DEHM) are some example of Eulerian model (Holmes and Morawska, 2006). The term Computational fluid dynamics (CFD) modeling is used for the computer based calculations of the mechanisms like heat transfer, fluid flow, chemical reactions etc (Vardoulakis et al). These phenomena demand very complex and lengthy calculations. MISKAM is an example of CFD model. CFD models demand a lot of input information and are difficult to use as well.

2.4.2. Street Pattern

The term street canyons have been used for those roads or streets which are not necessarily covered by continuous walls or buildings on both sides. The configuration of building, adjacent to particular streets affects dispersion of air pollutants in the street canyons. A regular street canyon has height/ width ratio around one. The avenue canyon term is used for those streets having low height adjacent buildings and have height/ width ratio around 0.5 (Vardoulakis et al., 2007). The OSPM can calculate pollutants level of roads with different height adjacent buildings, with wide range of height/ width ratios, buildings with openings and even open streets (Berkowicz et al., 1997).

2.4.3. Atmospheric turbulence

The meteorological conditions influence the flow of pollutants in the atmosphere. Different meteorological parameters (wind direction, wind speed, relative humidity, temperature and solar radiations) are important to monitor to study the pollutants concentration and behavior. Especially wind speed and wind direction are important parameters to model the dispersion of pollutants. Within the layer of 1000 m, wind direction and wind speed are influenced by vertical heights and surface roughness (Steinfeld, 1998). Solar radiations have direct correlation with ozone. At day time, ozone is produced as secondary pollutant, with considerable decrease in NOx, VOCs and some other primary pollutant, in the presence of solar radiations.

In 1961, Pasquill categorized atmospheric turbulence into six classes namely A, B, C, D, E and F. With A as the most unstable class, the stability of classes increases from A to F. The un-stability increases with low wind speed, high solar radiations at day time and cloud cover at night time. The turbulence increases with high wind speed, low solar radiations at less cloud cover at night time. An ideal condition for atmospheric turbulence would be at night time with no solar radiation, absence of clouds and very low wind speed (Turner, 1994). With advancement in studies, the more developed models are being used to model the turbulence of atmospheric pollutants.

MATERIALS AND MEHTODS

CHAPTER 3

3. Materials and Methods

The research is focused to point out different aspects of traffic related air pollution. The entire world is conscious about the traffic related air pollution and its health implications. The current research is designed not only to measure, analyse and model the air pollution levels but also to determine the transport sustainability in the city. "Sustainable Transportation" is one of the modern terms, introduced to improve the traffic related environmental, economic and social aspects. Transport sustainability index (TSI) of selected streets has been found out. Further a questionnaire survey has been conducted to determine the vehicular ownership, extent of use of different transportation modes, important factors to improve the public transport, main hurdles in the use of public transport and important potential initiatives to improve the use of public transport. To model the air pollution in different streets, operational street pollution model (OSPM) has been used, which is operational and applicable dispersion model for assessment of air quality of streets. The outline of the research work has been given in Fig. 3.1.

The outline of the research work (Fig. 3.1) explains research work under three main headings i.e. air quality monitoring through fixed air quality monitoring station, transport sustainability and air pollution modeling. Air quality monitoring is further divided into correlation analysis, ratio analysis, seasonal air quality index calculation, diurnal air quality trend assessment and assessment of monthly air quality pattern. Transport sustainability is further divided to selection of transport sustainability indicators, setting of requirements for different indicators, calculation of transport sustainability index and a questionnaire survey from four hundred people. Air pollution modeling requires background data of background air quality monitoring station at Town Hall, diurnal vehicular traffic count, street configuration and emission factor of different classes of vehicles. The correlation of observed and modeled data provides authenticity of modeled results. At the end a liaison between transport sustainability and air quality has been assessed.

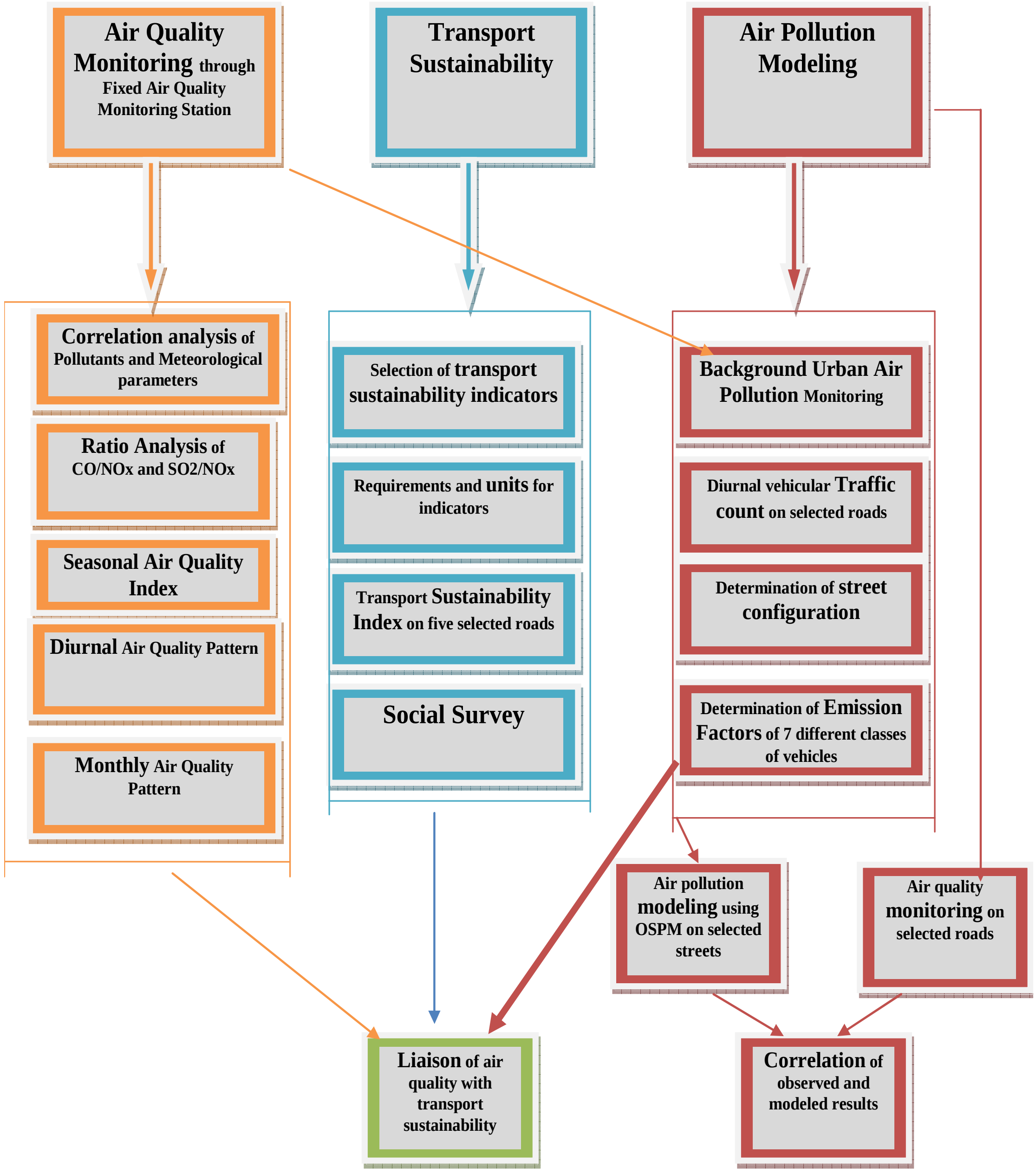

Fig. 3.1. Outline of research work

3.1. Urban emissions pattern in Lahore

3.1.1. Air quality analysis

Hourly air quality monitoring data for years 2007-2011 has been composed from air quality monitoring station at Town Hall and data of 2014-2015 was again monitored in co-ordination with EPA through monitoring station at Town Hall region. Fix and mobile air quality monitoring stations had been used to monitor the six major pollutants, and meteorological parameters. The air quality monitoring stations contain combined wind vane anemometer (KoshinDenkiKogyo Co, Ltd. Model KVS 501), solar radiation meter (Koshin Denki Kogyo Co, Ltd. Model SR-010), thermohygrometer (Koshin Denki Kogyo Co, Ltd. ModelHT-010), and data logging system (Horiba, Ltd. Model Special) to monitor meteorological parameters. The six major air pollutants like carbon monoxide (CO), ozone (O_3), sulfur dioxide (SO_2),oxides of nitrogen (NOx, NO and NO_2), respirable particulate matter ($PM_{2.5}$), and HCs (total hydrocarbons, non methane hydrocarbons and methane) were monitored through analyzers prescribed in Table 3.1. The $PM_{2.5}$ and PM_{10} has also been monitored through gravimetric method during monitoring of ambient air pollution other than air quality monitoring station. The hydrocarbon (HC) analyser needs uninterruptable power supply, any gap in electrical supply stops the working of hydrogen generator until it is manually started again. In case of the power supply provided by any generator to the mobile air quality monitoring station, care was opted to avoid the generator emission exposure to the air quality station. Moreover, proper routine calibration and maintenance was opted to run the air quality monitoring station. Filters of NOx, HC (CH4, NMHC, THC), O_3, SO_2 and CO analysers were changed within prescribed time. The sampling tape of $PM_{2.5}$ analyser was also set many times and changed on its completion.

Table 3.1. Detail of instruments of Air Quality Monitoring Station

Pollutant	Analyzer	Range	Method	Detection Limit
CO	Horiba Ltd; Model APMA-370	0~50 ppm	non-dispersive infrared ray method (ISO4224)	0.1ppm
NO/NO_2 /NOx	Horiba Ltd; Model APNA-370	0~1 ppm	Chemiluminescence (ISO7996) method	0.5 ppb
Sulfur dioxide	Horiba Ltd; Model APSA-370	0~0.5 ppm	U.V. fluorescence method (ISO10498)	1ppb
Ozone	Horiba Ltd; Model APOA-370	0~1ppm	UV photometry method	0.5 ppb
Hydrocarbon	Horiba Ltd; Model APHA-370	0~50 ppmC	Converter oven method	0.1 ppmC
$PM_{2.5}$	Horiba Ltd; Model APDA-370	0~5 mg m-3	β-ray absorption method (ISO6349)	----

A view of the air quality monitoring stations in Lahore has been shown in Fig. 3.2.a. and Fig.3.2.b.

Fig. 3.2.a. Air quality monitoring station (a) mobile station and (b) analyzers

Fig. 3.2.b. Fixed air quality monitoring stations (a) Town Hall and (b) Township

3.1.2. Air quality monitoring station

Lahore is located at 31°32′N 74°22′E. The city is located at an elevation of 217 m above sea level. The municipal area of Lahore is of 332 km^2. As a result of rapid urbanization, the area of the city has been extended to 1000 km^2 (Jalees and Asim, 2016). Two fixed air quality monitoring stations have been installed in Lahore to monitor air quality of Lahore. One of the stations is installed at the second floor of Town Hall building situated at northern main commercial area of Lahore with number of busy roads, markets and dense population. The second fixed air quality monitoring station has been installed in Quaid-i-Azam Township area i.e. southern residential area near Kotlakhpat industrial estate.

The Town Hall Air Quality Monitoring Station has been selected for data analysis. The fixed Air Quality Monitoring Station installed at Town Hall located at Multan road of Lahore, represents the ambient air quality of the main city of Lahore. The monitoring station has been located around 8 m height from the ground. The 8-meter height of the station is acquired to take sample of the air quality level in the area, instead to represent pollution level of any road or ground level. Moreover, effect of wind speed and wind direction on air quality is accommodated with that much height in the Town Hall area. Most of the main roads of Lahore lie within 1-3 km sphere of the station. The location of the two fixed Air Quality Monitoring Stations can be seen at "Fig. 3.3". The Air quality monitoring station in Quaid-i-Azam Township area has not been taken as background air quality monitoring station due to its location near Kotlakhpat industrial estate, instead Air Quality monitoring station at Town Hall has been taken as background air quality data source. The study area has been shown in Fig.3.4. And pictorial view of the selected roads has been shown in Fig.3.6. The location of Lahore, Pakistan on world map has been shown in Fig. 3.5.

Fig. 3.3. Location of automatic fixed air quality monitoring stations in Lahore

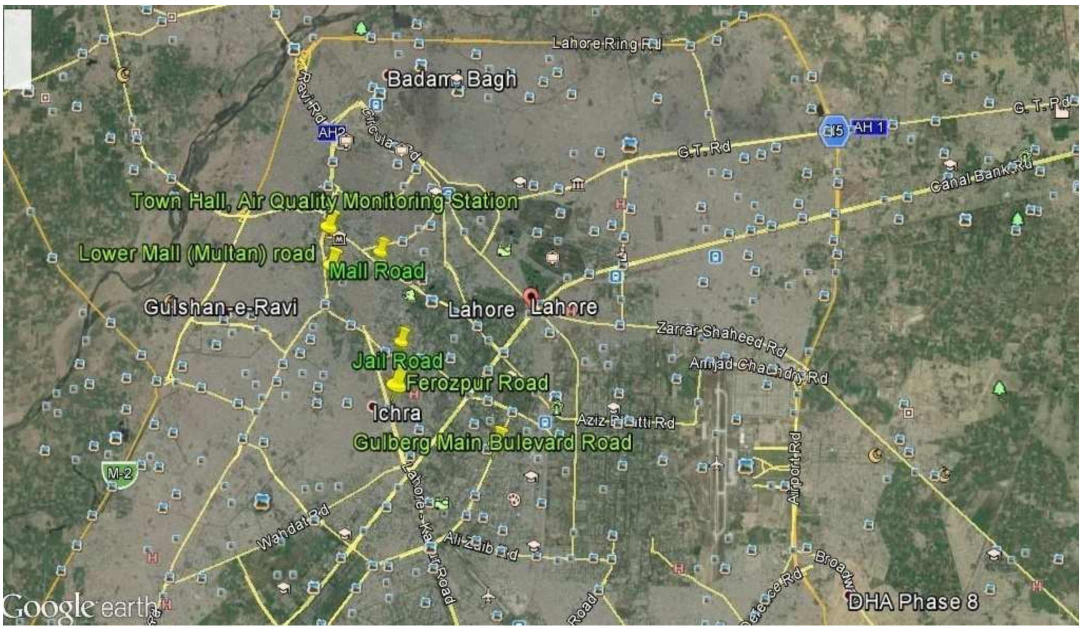

Fig. 3.4. Study Area (location of streets and air quality monitoring station)

Fig. 3.5. Location map of Lahore, Pakistan

Fig. 3.6. Google Location of five different roads along with pictures

3.1.3. Air quality index

The interpretation of AQI can be elaborated as clean, moderate, unhealthy and very unhealthy. The Pak-NEQS for O_3 (for 24 hour) has yet not been made available. The NEQS for O_3 (for 1 hour) have been revised from 180 to 130 (µg/m^3) and NEQS for $PM_{2.5}$ (for 24 hour) have been revised from 40 to 35 (µg/m^3), which are effective from January, 2013 (Officer et al., 2010). So, before January 2013, the index value would be calculated accordingly. A projected AQI has been given in Table 3.2 (Abrar et al., 2014).

The Air Quality Index (AQI) was calculated according to “eq. 3.1”.

Air Quality Index= $[(NO_2/80) + (SO_2/120) + (O_3/130) + (CO/5) + (PM_{2.5}/35)]/5 \times 100$ (3.1)

Table 3.2. Air Quality Index

AQI	0–50	50-100	101-150	151-200	201-300	>300
Air Quality	Clean	Moderate	Unhealthy for sensitive	Unhealthy	Very Unhealthy	Hazardous

3.2. Transport sustainability of Lahore

Like many other cities of Pakistan, Lahore city has been emerged without taking into account many sustainability measures. Sustainable development is not necessarily a search for a strict balance. It is a dynamic idea which promotes that change is very much natural phenomena for human society. As the scientist mostly lacks formation of policies on the basis of scientific findings (Laing and Wallis, 2016). There is need to involve all the stake holders (policy makers, experts, public and scientists) to know and implement the modern tools of transport sustainability in the city instead of using conventional and ordinary measures only.

3.2.1. Transport sustainability index

The indicators for transport sustainability have been chosen according to the local requirements and resources. The participation from public, experts as well as from research studies have helped to choose indicators according to local needs within available resources. To calculate the transport sustainability of five selected streets (Ferozepur road, Gulberg road, Jail road, Mall road, Multan road), 35 indicators of transport sustainability have been set. The indicators of transport sustainability are given in Table 5.2 in Chapter V. Each indicator has been given weight-age as 0, 0.5 or 1 according to acceptable fulfillment of criteria, set in consultation with experts and stake holders.

3.2.2. Social survey

A questionnaire has been developed to collect data from public about their vehicular ownership, mode of daily trips, hurdles in the use of public transport, opinion to promote public transport, usefulness of different methods to create awareness to promote public transport and their comments have also been taken at the end of questionnaire. Data has been collected from 400 stakeholders from different walks of life. 96 females and 308 males gave their data and opinion through questionnaire. The questionnaire is attached as Annexure-I.

Following tasks were attained through questionnaire survey,

- Collection of vehicular ownership data,
- Study of the main hurdles in the use of public transport,
- Study of the different modes of transportation,
- Importance of the factors in the use of public transport,
- Effectiveness of the different factors and initiative to promote the use of public transport,

- Public opinion regarding effectiveness of different initiatives to promote public transport.

No woman has been found to use motorcycle during the social survey. People were interviewed mostly from different public and private offices as well as universities. The choice has been made as very less important, less important, fairly important, important and very important from 1 to 5 respectively to fill the questionnaire. The factors were ranked by giving them weight-age out of 5 grades.

3.3. Air quality modeling

3.3.1. Urban air quality modeling of streets

The air quality modeling of a street requires a lot of data to model the air pollutants in a certain street. The well-known Operational Street Pollution Model (OSPM) has been used to model the air quality in different streets. The OSPM software requires following information to model the street emissions,

- Background urban emissions and meteorological data,
- Diurnal vehicular traffic count with number of each class of vehicles in different hours,
- Average speed of vehicle,
- Fuel specifications, engine type and average speed of vehicle to count emission factors of vehicles,
- Street configuration data like, street width, orientation and building height.

The background urban emissions data has been taken from air quality monitoring station at Town Hall building at Multan. The street configuration and diurnal vehicular traffic data was collected through field survey. The emission factors of vehicles were calculated by providing 1990 level of fuel and 2000 model level of vehicles in Europe to the OSPM software. The 1990 level of fuel and 2000 level of vehicles of Europe were selected due to similarity with current conditions. The Emission factor of SO_2 were calculated through a previous study due to similar conditions. The modeled results were compared with the observed results. The correlation of observed and modeled results was measured to check the effectiveness of modeling.

3.4. Statistical analysis

The statistical techniques are used through SPSS 22nd version. Correlation analysis of air pollutants and meteorological parameters has been performed through SPSS software. The questionnaire survey (regarding transport sustainability) of 400 citizens, including 308 men and 96 women has been analyzed through SPSS software. The questions involved five different levels of answers from interviewee like very less effective, less effective, fairly effective, effective and very effective from 1 to 5 respectively, to fill the questionnaire. Similarly, correlation of modeled and observed results on five selected roads of Lahore has also been determined through SPSS.

RESULTS AND DISCUSSION
URBAN AIR QUALITY OF LAHORE

CHAPTER 4

4. Urban air quality of Lahore

This chapter is an attempt to find out diurnal & monthly mean pattern of air pollutants, their interdependence and their dominant sources through hourly and monthly data analysis. Different statistical techniques, like ratio analysis and correlation have been applied to discover dominant sources of pollutants and their inter-relationship with each other.

4.1. Air quality index

Ambient air quality data of Lahore for the years 2007-2011 and 2014-2015 has been analyzed to find out pattern and sources of representative six air pollutants. Average concentration, monthly mean pattern, seasonal and diurnal variations were analyzed for the hourly data of each pollutant. Air Quality Index (AQI) remains low (~74 to ~85) from June to August due to heavy rain, relatively high wind speed (~1.59 to ~1.85 monthly average), dispersion because of high temperature and high solar radiations. Similar results have been observed with an improved air quality index in northern china, in summers. (Gong et al., 2015). But the ozone levels remain high during summer season due to relatively high solar radiations. High levels of ozone (UV absorbent aerosol) have also been confirmed by OMI onboard satellite data, in Pakistan during summer season (Tariq and Ali, 2015). Highest AQI (~132 to ~185) has been observed from November to February due to inversion at low wind speed (< 1.5 m/s monthly average), low temperature (~ 15-21°C monthly average) and low solar radiations (~104-140 W m^{-2} monthly averages), due to heavy fog during December and January**.** Another reason of highest air quality index during fall season can be due to burning of crops residue in south-western India and eastern Pakistan.

The wind direction during winter season remains mostly in south-east direction, which can also be a reason for contribution to pollution in Lahore from number of polluted steel industries in northern part of the Lahore city and industrial clusters in Sheikhupura and Gujranwala. The steel industries are mostly located in Badami Bagh, Misry Shah, Daroghay Wala and around Band road area in Northern part of Lahore. The map of Lahore has been given in "Fig. 3.2".

4.2. Air quality data analysis

For the data analysis, the data of day-time (7:00 AM to 5:00 PM) has been taken for analysis of ozone and its precursors. The data of a sunny and clear day has been taken. The mean concentration of the ozone, other pollutants and meteorological parameters are given in the Table 4.1.

Table 4.1. Mean values of different pollutants & meteorological parameters (7 AM to 5 PM)

Variable	Unit	Min.	Max.	Mean Value
NO	$\mu g\ m^{-3}$	0.02	8.10	1.93
NO_2	$\mu g\ m^{-3}$	20.83	48.21	28.52
NOx	Ppb	10.92	30.05	16.14
CH_4	Ppb	1636.21	5000.00	2210.61
NMHC	Ppb	211.80	1587.33	735.85
CO	$mg\ m^{-3}$	0.35	1.02	0.68
SO_2	$\mu g\ m^{-3}$	22.18	65.95	42.64
O_3	$\mu g\ m^{-3}$	29.69	204.00	122.5
$PM_{2.5}$	$\mu g\ m^{-3}$	54.00	244.00	155.07
Wind Speed	m/s	0.92	2.87	1.72
T	°C	28.33	42.25	37.68
RH	%	18.02	50.65	30.66
Solar radiation	$W\ m^{-2}$	135.59	766.40	539.35

The day is dry and hot with low mean RH (30.66), high solar radiations (about 680 W m^{-2}) and high mean temperature (around 38 °C). Wind speed remained low (mean value = 1.72 m/sec) as a routine matter in semi-arid regions. NO remained almost nil (mean value = 1.93 µg m^{-3}) during sunny hot days due to its conversion to NO_2 (mean value = 26.8 µg m^{-3}) in the presence of high concentration of O_3 (mean value = 122.50 µg m^{-3}). Concentration of CH_4 remained low (mean value =2210.61 ppb) than its natural level (around 3000 ppb) due to its consumption as precursor of ozone. Mean value of $PM_{2.5}$ (155.07mg m^{-3}) remained high due to high amount of un-burnt carbon from vehicular exhaust emissions in the atmosphere.

4.3. Correlation analysis

The correlation of different air quality parameters has been given in Table 4.2.

Table 4.2. Correlation analysis of ambient air variables

		NO	NO_2	NOx	CH_4	NHMC	CO	SO_2	O_3	$PM_{2.5}$	WS	T	RH	Solar radiation
	NO	1	.946**	.741**	.953**	.416	.917**	.556	-.825**	.163	.058	-.725*	.616*	-.614*
	NO_2	.946**	1	.871**	.978**	.254	.912**	.571	-.675*	.200	-.084	-.634*	.496	-.660*
	NOx	.741**	.871**	1	.797**	.039	.734*	.363	-.520	.072	-.138	-.401	.249	-.635*
	CH_4	.953**	.978**	.797**	1	.214	.892**	.576	-.714*	.094	-.003	-.710*	.571	-.717*
	NMHC	.416	.254	.039	.214	1	.336	.185	-.238	.497	-.157	-.135	.184	.245
Pearson Correlation (r value)	CO	.917**	.912**	.734*	.892**	.336	1	.809**	-.758**	.443	.224	-.805**	.737**	-.466
	SO_2	.556	.571	.363	.576	.185	.809**	1	-.516	.654*	.519	-.820**	.841**	-.160
	O_3	-.825**	-.675*	-.520	-.714*	-.238	-.758**	-.516	1	-.004	-.491	.824**	-.763**	.525
	$PM_{2.5}$	.163	.200	.072	.094	.497	.443	.654*	-.004	1	.045	-.189	.282	.487
	WS	.058	-.084	-.138	-.003	-.157	.224	.519	-.491	.045	1	-.678*	.769**	-.088
	T	-.725*	-.634*	-.401	-.710*	-.135	-.805**	-.820**	.824**	-.189	-.678*	1	-.978**	.523
	RH	.616*	.496	.249	.571	.184	.737**	.841**	-.763**	.282	.769**	-.978**	1	-.364
	Radiation	-.614*	-.660*	-.635*	-.717*	.245	-.466	-.160	.525	.487	-.088	.523	-.364	1

**Correlation is significant at the 0.01 level (2-tailed)., * Correlation is significant at the 0.05 level (2-tailed)

O_3 has significant negative correlation with NO, NO_2, NOx, CH_4, CO, and RH (r-value> -0.5); and has significant positive correlation with T and solar radiations (r-value> 0.5). The level of tropospheric ozone is highly dependent on solar radiations and atmospheric temperature (Swackhamer, 1993). NO has significant positive correlation with NO_2, NOx, CH_4, CO and RH (r-value> 0.5 for each); and has negative correlation with O_3, T and solar radiations (r-value> -0.5 for each). NO concentration is almost negligible from 7 am to 5 pm in the summers due to its conversion into NO_2 by reacting with abundant O_3 produced by different sources like CO, NO_2, VOCs and NMHCs, in the presence of sunlight. NO_2 has significant positive correlation with NO, NOx, CH_4, CO and SO_2 (r-value> 0.5 for each); and has significant negative correlation with O_3, T and solar radiations (r-value> -0.5). At day-time, almost all the NO has been converted to NO_2 by reacting with O_3 in the presence of sunlight. The dominant sources of nitrogen oxides are diesel engines and 4 stroke petrol engines among the mobile sources (Yasar et al., 2013). NOx have significant positive correlation with NO, NO_2, CH_4, CO and SO_2 (r-value> 0.5 for each); and have significant negative correlation with O_3 and solar radiations (r-value> -0.5). CH_4 has significant correlation with NO, NO_2, NOx, SO_2 and RH (r-value> 0.5 for each); and has significant negative correlation with O_3, T and solar radiations (r-value> -0.5). NMHC have no significant correlation with any of the parameters. CO has a significant positive correlation with NO, NO_2, NOx, CH_4, SO_2 and RH,(r-value> 0.5 for each), and has significant negative relation with O_3 and T (r-value> -0.5). Rasheed also has observed a significant positive correlation between CO and NO, NO_2, NOx, CH_4, SO_2 and negative correlation between CO and O_3 (Rasheed et al., (2015). A strong correlation amongst the NO, NO_2, NOx, CH_4, CO and SO_2 suggest that the dominant sources of these pollutants are direct or primary in nature. The results of vehicular exhaust emission monitoring suggests that the major sources of CO are CNG, LPG and petrol engines. Diesel engines generates relatively very low amount of CO. Ambient CO emissions always remains within the permissible limit of 5 mg m^{-3} = 5000 µg m^{-3}. Therefore, CO emissions may not be considered low in terms of µg m^{-3} units. The significant positive correlation between CO and NO (r = 0.72; *p*-value < 0.01) shows a common source for both of them. CNG engines are a main common source for the emission of CO and NO (Yasar et al., 2013). Pakistan has the highest number of vehicles using CNG fuel (Yasar, et al., 2013). CO produces O_3 through number of chemical reactions with hydroxyl radicals and NO in the polluted environment in the presence of sunlight. The dominant sources of CO emissions are two strokes and four stroke petrol, CNG and LPG vehicles. Diesel engines produces only minute amount of CO emissions (Yasar, et al., 2013).

The major source of SO_2 emissions are diesel engines and two stroke LPG vehicles (Yasar et al., 2013). SO_2 has significant positive correlation with NO, NO_2, CH_4, CO, $PM_{2.5}$, WS and RH (r-value> 0.5 for each); and has significant negative correlation with O_3 and T. Correlation of SO_2 with WS suggests that point sources can be a dominant source for SO_2 emissions. The common source for CO and SO_2 are LPG engines.

$PM_{2.5}$ has significant positive correlation only with SO_2 (r-value> 0.5). The correlation of $PM_{2.5}$ with SO_2 suggests that most part of these pollutants originates from fresh emissions from mobile and point sources. Some amount of $PM_{2.5}$ may be produced by chemical conversion of SO_2 into particles. The similar trends have been reported by Aneja et al., (2009). A negative correlation of $PM_{2.5}$ with T has already been reported (Tiwari et al., 2012). Some researchers have reported conversion of semi volatile components from particle phase to gas phase at certain high temperature (Sheehan and

Bowman, 2001; Aw and Kleeman, 2003; Dawson et al., 2007; Kanakidou et al., 2007). Yasar has reported high smoke opacity for most of the diesel engines, which are a dominant source for $PM_{2.5}$. Diesel engines are dominant source for SO_2 and $PM_{2.5}$ emissions, which explains high correlation between $PM_{2.5}$ and SO_2 (Yasar, et al., 2013).

RH has significant positive correlation with NO, CO, SO_2 and WS (r-value> 0.5); and significant negative correlation with O_3 and T (r-value> -0.5). In fact, RH has significant negative correlation with T and has very little correlation with other pollutants. The pollutants may have very minute correlation with WS and RH. In other words, it is difficult to explain the correlation of pollutants with WS and RH in the presence of many other factors as well. In the winter season, excess amount of ammonia at low temperature and high relative humidity, upturns PM by producing nitrate particles (Pitchford et al., 2009; Raja et al., 2010). Temperature has significant negative correlation with NO, NO_2, CH_4, SO_2, WS and RH (r-value> -0.5); and has significant positive correlation with solar radiations and O_3 (r-value> 0.5). Similar results have been obtained in previous studies like by Rasheed and Jacob (Jacob and Winner, 2009; Rasheed et al., 2015). This explains the production of ozone in the presence of solar radiations in the presence of precursors of O_3.

4.4. Ratio analysis

High ratios of CO/NOx and low ratios of SO_2/NOx indicate that the mobile sources are the major source of CO, and point sources are the major source for SO_2 emissions. The production of NOx is associated with high temperature during fossil fuel burning. Therefore, NOx are usually produced at high temperature in 4-stroke petrol engines and diesel engines. However, SO_2 are dominantly produced due to high sulfur contents in fuel. High sulfur contents (0.5-1%) are present in diesel available in Pakistan. Therefore diesel engines are the major anthropogenic source of SO_2 emissions in Lahore (Yasar et al., 2013). As NOx are abundantly produced by both 4-stroke petrol engines as well as diesel engines at high temperature; therefore, concentration of NOx usually remains high in Lahore city. An emission inventory has been provided by (Darras et al., 2010; Klimont et al., 2013) for CO, SO_2 and NOx. The data of ratio of CO/NOx and SO_2/NOx has been given in the Table 4.3. The Table 4.3 has also provided the ratio analysis of CO by NOx and SO_2 by NOx, provided by different studies like Denver, CO, US (Parrish et al., 1991); Boulder, CO, US (Goldan et al., 1995) Raleigh, NC, US (Aneja et al., 1997) and New Delhi, India (Aneja et al., 2001). The above said studies have similar trend of ratios of CO/NOx and SO_2/NOx as do in the current study.

Table 4.3. Ratio analysis based on average emissions and/or ambient data.

Region	**Source**	**CO/NOx**	**SO_2/NOx**
Eastern US	Ambient	4.3	0.94
	Mobiles	8.4	0.05
	Point Sources	0.95	1.8
Pennsylvania Area	Ambient	2.6	1.7
	Mobiles	7.8	0.05
	Point Sources	0.8	2.3
Western US	Ambient	7.3	0.19
	Mobiles	10.5	0.05
	Point Sources	0.18	0.44
Denver Metropolitan area	Ambient	7.3	0.19
	Mobiles	10.5	0.05
	Point Sources	0.18	0.44
Raleigh, NC	Ambient	16.3	0.73
New Delhi, India	Ambient	50	0.58
Lahore (during May)	Ambient	14.103	0.524
	Mobiles	7.699	0.263
	Point Sources	0.759	0.407

1 ppb NOx = 1.91 $\mu g/m^3$, CO, NOx and SO_2 have been taken in $\mu g/m^3$ units

4.5. Air quality monitoring at different spots

The urban background emissions data has been provided by the air quality monitoring station installed at Town Hall building. According to Katulski, it is impossible to monitor the spatial and temporal variations in the atmosphere on the basis of a single monitoring site (Katulski et al., 2011). Therefore, a monitoring program was launched to monitor air quality of different sites. The following different categories were monitored,

- Traffic Hotspots,
- Road Side,
- Industrial Area,
- Urban Background Station,
- Rural Area

The average monitoring results are given in Table 4.4, which may act as a comparison of different spots of urban emissions level in Lahore.

Table 4.4. Comparison of air quality at different locations in Lahore, Pakistan

	NO µg/m^3	NO_2 µg/m^3	NOx ppb	CO mg/m^3	SO_2 µg/m^3	$PM_{2.5}$ µg/m^3
Traffic Hotspots	52.655	130.724	115.935	2.508	70.536	294.288
Road Side	43.642	108.503	104.721	1.54	52.69	202.938
Industrial Area	38.075	95.528	88.393	0.1282	68.793	191.644
Background Station	27.563	71.274	60.327	1.625	60.328	174.222
Rural Site	8.55	22.871	18.443	0.0892	19.79	122.234
NEQS	40 (24 hour)	80 (24 hour)	-	5 (08 hour)	120 (24 hour)	35 (24 hour)

4.6. Analysis of ozone formation

Ozone is a secondary pollutant. The primary sources for ozone are CO, VOCs, CH_4, NO_2 and solar radiations. A large amount of O_3 has also been produced around high voltage electric lines. Some countries also claim high amount of O_3 due to trans-boundary movements. It has been observed that during summers, almost all the NO has been converted to NO_2 by reacting with O_3, being produced by different chemical reactions of CO, CH_4, VOCs and NO_2 in the presence of sunlight. Therefore NO concentration remains almost nil in the presence of high solar radiations at day-time in summers. A possible dynamic equilibrium between NO and NO_2 has been given in "eq. 4.1" (Seinfeld and Pandis, 2016).

$$NO + O_3 \leftrightarrow NO_2 + O_2 \quad (4.1)$$

NO_2 reacts with oxygen in the presence of sunlight to produce O_3 and NO. As the NO concentration is almost nil at day-time in summers, it may be assumed that O_3 has been produced in abundant amount by different primary sources to keep the reaction forward according to Le Chatlier principle i.e. almost all the NO has been converted to NO_2 due to abundant amount of O_3 produced by number of primary sources, in the presence of sunlight. Therefore, it can be assumed that O_3 concentration measured at day-time in summers (high solar radiations) is that O_3, which has been produced by sources other than NO_2 or NOx; as the amount of O_3 produced by NO_2 has been consumed by NO. Or it may be assumed that whenever the value of NO is negligible, the amount of O_3 produced would be that amount of O_3, which is produced by sources other than NO_2 or NOx. Another assumption is that, the sources like VOCs, CO, CH_4 convert NO to NO_2 and higher oxides of nitrogen. The production of ozone as secondary pollutant has been described by many old and recent studies (White et al., 1976; Jenkin and Clemitshaw, 2000; Attri et al., 2001). The NO_2 is further photo-lysed to produce O_3. At day-time, the value of NO is negligible due to its conversion to NO_2. The value of NO_2 or NOx has been found to be as high as the O_3 value. Therefore, a significant positive correlation is observed between NO_2 and O_3 or between NOx and O_3 during day-time. Dependence of ozone on primary pollutants like VOCs and NOx has also been described by many previous and recent studies (Jenkin et al., 2000; Attri et al., 2001; Martin et al., 2015). To assess the extent of dependence of Ozone on other variables, paired sample t test has been applied on data. The results of paired sample t test are given in Table 4.5.

Table 4.5. Comparison of dependents through Paired Sample t Test

		T	P
Pair 1	NO - O_3	-4.872	0.005
Pair 2	NO_2 - O_3	-3.923	0.011
Pair 3	NOx - O_3	-4.354	0.007
Pair 4	CH_4 - O_3	16.787	0.000
Pair 5	$PM_{2.5}$ - O_3	1.811	0.130
Pair 6	WS - O_3	-4.977	0.004
Pair 7	T - O_3	-3.713	0.014
Pair 8	RH - O_3	-3.668	0.014
Pair 9	Solar radiation - O_3	15.505	0.000

The t value of all the precursors of ozone like NOx, CH_4, temperature and solar radiation is non-zero. The p value of NO, NO_2, NOx, T and solar radiations are less than or very close to 0.01 (99% confidence level), indicating their significant effect for Ozone. For $PM_{2.5}$ p-value is 0.13 indicating no significant dependence of ozone on $PM_{2.5}$. Although p values for wind speed and RH are close to 0.01, but practically, RH has no significant relation for ozone and dependence of ozone on wind speed depends on wind direction. Wind speed is a very important factor in dilution of urban air pollution. Whenever wind speed is increased upto $\geq$ 2 m/sec, a strong dilution has been observed in urban air pollution accordingly.

4.7. Diurnal and monthly mean pattern

It has been observed that all the primary pollutants like CH_4, NMHC, CO, NO, NO_2, NOx, SO_2 and $PM_{2.5}$ have positive correlation with each other and negative correlation with O_3. Peak value of O_3 has been observed during day-time due to presence of high solar radiations especially in summers. In the absence or reduction of light at night, almost nil or minimum values of O_3 have been observed. The diurnal variations remain same in every season and all months of the calendar. The value of O_3 has been observed very high during summer noon due to high solar radiations. Maximum pollution of primary pollutants has been observed from November to February due to low solar radiations and low photochemical reactions to produce O_3. The diurnal variation of O_3 and Other pollutants (on 1st May) has been given in "Fig. 4.1". The significant correlation of O_3 with temperature and solar radiations has been described in "Fig. 4.2". The similar dependence of O_3 on solar radiations has also been described by many researchers like Swackhamer and Tariq (Swackhamer, 1993; Tariq and Ali, 2015).

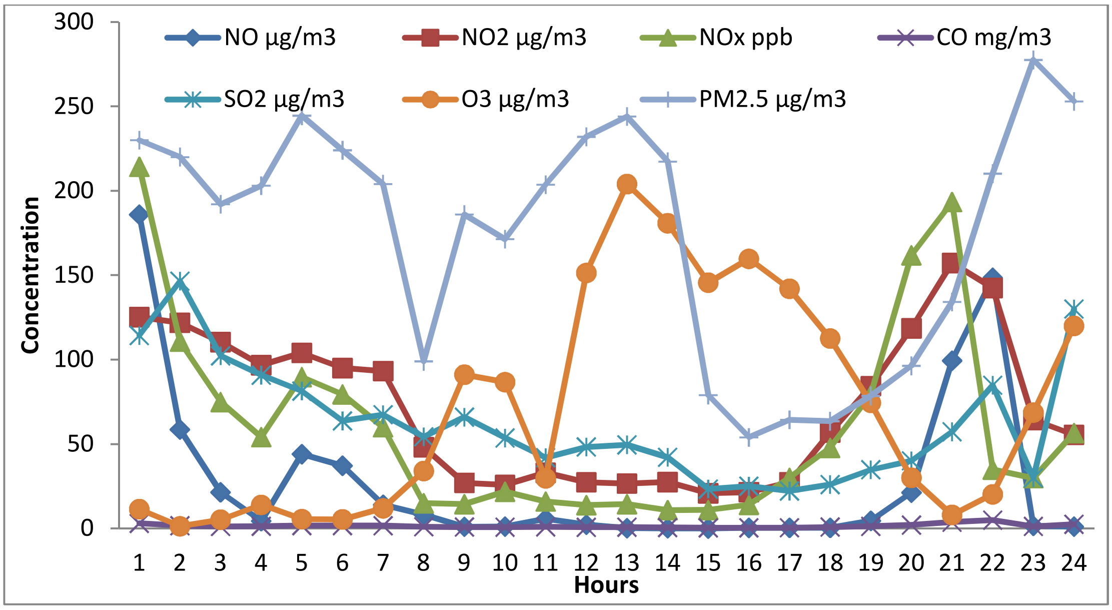

Fig. 4.1. Diurnal trend of air quality pollutants

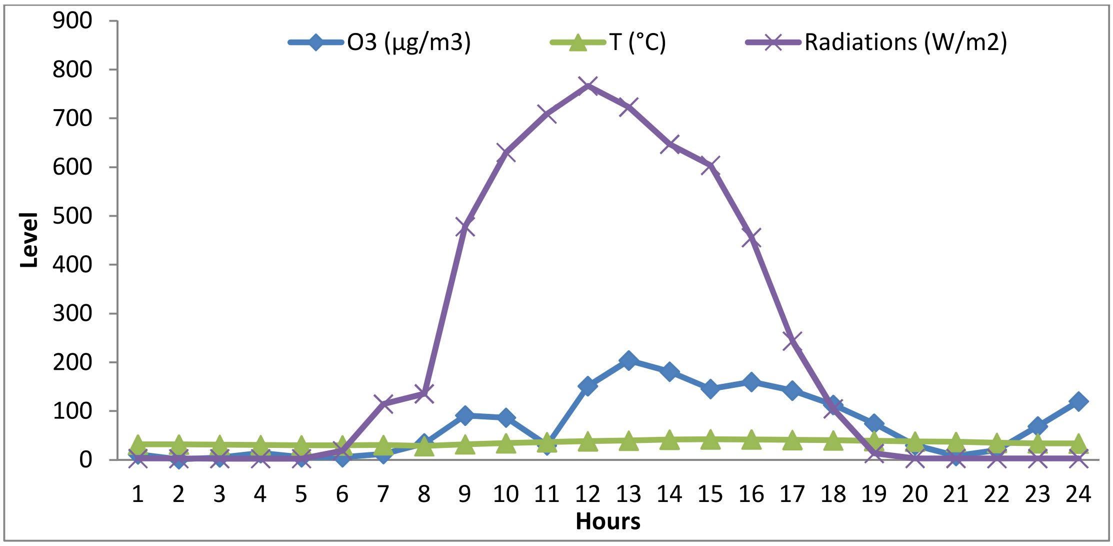

Fig. 4.2. Diurnal trend of ozone, temperature (T) and solar radiations

4.8. Seasonal pattern of Ozone and other pollutants

There are five different seasons in Lahore. The two main seasons are winter and summer with extreme climatic conditions. As already discussed, O_3 has a significant correlation with temperature (r = 0.7) as given in Table 4.2. The value of O_3 remains high during summers due to high solar radiations. High levels of O_3 as UV absorbent have also been confirmed by OMI (ozone monitoring instrument of NASA) onboard satellite data, during summers, especially in southern parts of Pakistan (Tariq and Ali, 2015). The concentration of precursors of O_3 remains high during winter season mainly due to low solar radians. The main features of winter season in Lahore are,

- Low wind speed,
- Low solar radiations/ temperature,
- And less precipitation.

This favors accumulation and inversion of air pollutants. Therefore, highest air pollution has been found from November to February in Lahore as a semi-arid region. But concentration of secondary pollutant O_3 remains low in winter season due to low solar radiations. The summer season comprises of

- Relatively high wind speed,
- High solar radiations/temperature,
- Monsoon rains during July and August.

All these factors results in dispersion and washout of air pollutants. But O_3 concentration remains high during summers due to high solar radiations. Similar trend has also been observed by SUPARCO for $PM_{2.5}$ (highest in October and low in July) in 2006 (Shahid et al., 2015). The monthly pattern of O_3 and other pollutants have been elaborated in “Fig. 4.3”.

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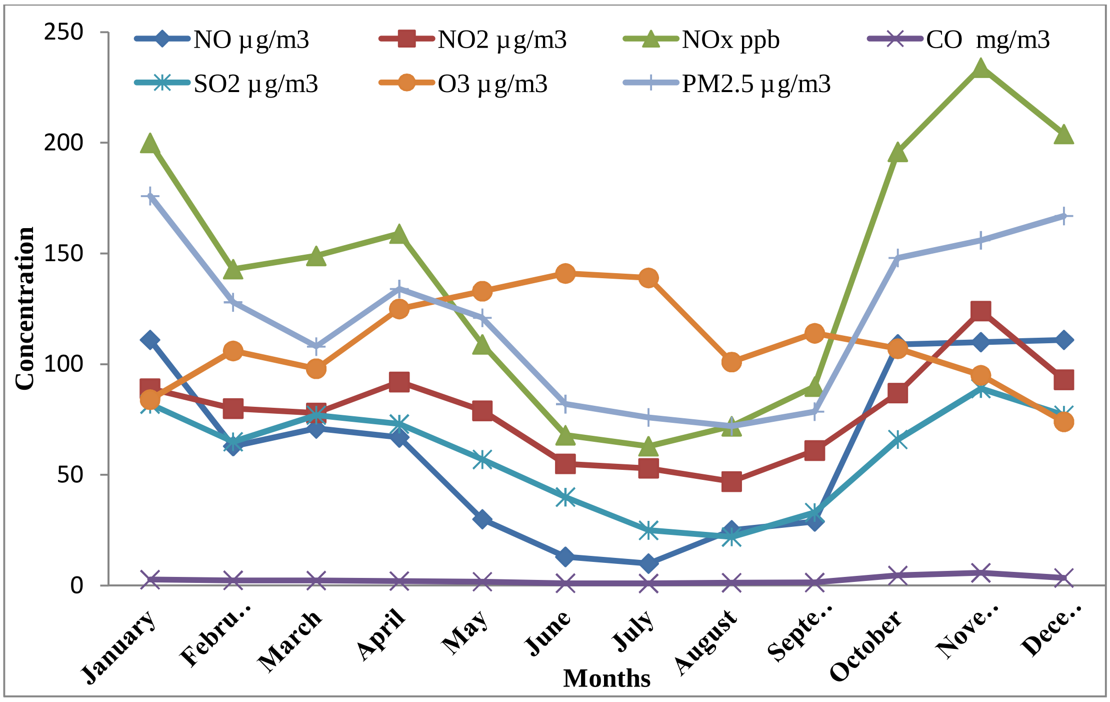


Fig. 4.3. Seasonal/Monthly pattern of air quality pollutants in Lahore

4.9. Summary

The annual average concentrations of $PM_{2.5}$ and NO are exceeding the Pak-NEQS. The NEQS for $PM_{2.5}$ are very strict for a semi-arid region as $PM_{2.5}$ levels are exceeding strict NEQS of 35 µg m-3, even in rural areas around Lahore city. The 24 hours and annual Pak-NEQS have not been established for ozone, although its concentration remains too high during summers. Mobile sources are main contributor to high concentrations of NO. The hourly average levels of ozone exceed the Pak-NEQS during the summer season. CO and SO_2 are found to remain in compliance with the Pak-NEQS for the entire calendar year. The monthly pattern of pollutants show that AQI remains high during winter season due to relatively low washing effect (low rain), low wind speed and high inversion. Similar trend has also been observed by SUPARCO for $PM_{2.5}$ (highest in October and low in July) in 2006. More over the dominant wind direction from south-east side enables polluted steal industry to contribute to pollution of Lahore in winter. But ozone levels remain low during winter season due to low solar radiations. The diurnal trend of pollutants is similar to monthly pattern i.e. AQI remains low at day-time at high T and solar radiations. The concentration of primary pollutants like NO, NO_2, NOx, CO, SO_2, CH_4, NMHC and $PM_{2.5}$ remains low at day-time due to their use as precursor of O_3, dispersion effect and many other factors. The ozone level remains high at day-time (like in summers) due to high solar radiations and presence of high concentration of its precursors.

Ozone has positive correlation with T and solar radiations; and has negative correlation with most of the pollutants like NO, NO_2, NOx, CO and CH_4. Wind speed, T and solar radiations have negative correlation with primary pollutants. Wide range of fluctuation in NO concentration has been observed in the presence and absence of solar radiations. Ozone in the presence of solar radiations has reduction effect for most of the pollutants other than $PM_{2.5}$ and NMHC. The correlation studies suggest that the dominant sources of the primary pollutants are fossil fuels, either from mobile sources or point sources. The 4 stroke petrol engines are a common source for CO, NO, NO_2 and NOx; which are precursors of O_3. Diesel engines are major common source for NOx, SO_2 and $PM_{2.5}$. SO_2 emissions mostly remain in compliance with NEQS in Lahore, as most of the vehicles use petrol as fuel. As NOx are abundantly produced by both 4-stroke petrol engines and diesel engines, the concentration of NOx mostly remains high in Lahore city. The ratio analysis showed that mobile sources are the major sources for CO and NOx emissions, while point sources are the major source for SO_2 emissions in the Town Hall area of Lahore.

RESULTS AND DISCUSSION
EVALUATION OF TRANSPORT SUSTAINABILITY

CHAPTER 5

5. Evaluation of transport sustainability

This chapter is intended to find out sustainable transport indicators, social survey and transport sustainability index for the five roads of Lahore, Pakistan. The indicators of transport sustainability have been discussed under the main heads like, shifting of modes from private to public vehicles, land use planning and sustainable operations. A social survey has been conducted through a questionnaire.

5.1. Selection of indicators

Different studies have described number of indicators for sustainable transport system but the selection of clear indicators is always difficult, either due to lack of clear targets or due to the deficiency of systematic process (Smith et al., 2013a). Recently different necessary steps have been suggested by European commission in a research project. The main findings of project are promotion of lighter & efficient vehicles with advanced combustion engines, reduction in road transport, promoting GHGs legislations, shift towards electric & hydrogen fuel vehicles, social & economic research and planning and measures to reduce transport demand (Luè, et al., 2016). In this study, three main pillars of sustainability: economics, environment and social indicators have been discussed under heads like shifting of modes, land use planning and sustainable operations. The economic indicators include cost as well as contribution to the economy of using car fleet. Cost is associated with health issues and accidents. Economic contribution deals with profitable manufacturing of cars and services sector. Regarding social domain employment is one of the main benefits of this sector. Third factor is environmental pollution in the form of gaseous emissions and noise. It is worth mentioning that disbenefits of car fleet emissions, road congestion and noise are often not shared equally. Health effects of climate change and air pollution are one of the examples (Smith et al., 2013b).

Many experts believe that fossil fuel is socio-natural metabolism for capitalism (McCarthy, 2015). But there is need to find out renewable resources for new developments. Therefore, the third strategy focuses on the use of sustainable operations. Sustainable operations include use of CNG or LPG fuel for cars and buses, use of biodiesel for diesel engines and use of hybrid technology for motorcycles and cars (Shiau, 2012). A lot of research work has done on improvement of engine emissions by introduction of certain fuels as depicted in recent studies by Mofijur, Imdadul, Kumar and Ali (Mofijuret et al., 2016; Imdadul et al., 2016; Kumar et al., 2016; Ali et al., 2016). The description of indicators selected for calculation of transport sustainability index has been given in Table 5.1.

Table 5.1. Selected indicators for assessment of transport sustainability index

Primary Indicators	Secondary Indicators	Tertiary Indicators	Quaternary Indicators
Shifting Modes	✓ Reducing the use of Private Vehicles ✓ Promoting the use of Public Transportation	✓Promoting Walk ✓Promoting Bicycle ✓Improving Transit Services	✓Availability of sidewalks ✓Availability of pedestrian signals ✓Availability of crosswalks ✓Availability of ITS pedestrian treatments ✓Disability infrastructure ✓Short block lengths (≤ 800 ft.) ✓Streets in a grid pattern (Repeated) ✓Guide signs ✓Dedicated bicycle lanes on the road ✓Dedicated bicycle lanes off the road ✓Availability of bike sharing services/bike rental ✓Bike service stations ✓Short-haul shuttle/ circulators/ local bus ✓Bus rapid access (Metro Bus) ✓Light rail access /Commuter rail access ✓Fast connection with neighbor cities ✓Park and ride facilities at rail and bus rapid/bus stations ✓Suitable headways (30 mins/20min/10 min ✓for rail local bus and metro bus respectively or shorter) ✓Dedicated bus lanes

Primary Indicators	Secondary Indicators	Tertiary Indicators	Quaternary Indicators
			✓Signal free tracks (presence of overhead bridges and underpasses) ✓Affordable fair ✓No. of people using private cars ✓Location within ¼ to ½ mile of Public Transport
Land Use Planning	✓ Length Reduction ✓ Trip Reduction ✓ Fuel Saving ✓ Time Saving	✓Mixed-use Buildings ✓Transit-Oriented Developments ✓IT instead of Travel ✓Domestic Vegetables ✓Accessible School/Parks/ Market/Parking ✓Speed Calming Measures ✓Prohibition of migration from neighbor cities (localized education, localized employment)	✓Mixed-use buildings ✓Parks/playgrounds /open and green spaces ✓Veggie gardens/ kitchen Gardens ✓Speed control measures - vertical treatments. ✓Speed control measures - horizontal treatments ✓Volume control measures ✓E-commerce/E-billing/video conferences ✓Fast connection with neighbor cities (Repeated) ✓EIAs (Public Participation) ✓Road width ✓Repair and Maintenance of roads ✓Short block lengths (≤ 800 ft.) ✓Streets in a grid pattern
Sustainable Operations	✓ Use of renewable energy resources ✓ Better fuel Quality	✓ Promote renewable energy resources ✓ Improve fuel Quality	✓Use of CNG Buses ✓Low power systems /Alternative power systems ✓Low sulfur and benzene content in fuel

5.2. Transport sustainability index

Lahore is an old city. The main infrastructure of the city has not been developed according to the modern design of transport sustainability. Mix traffic is main feature of road traffic in Lahore. There are no fixed lanes for bicycles or buses. It is very difficult to walk along the roads, cross the roads or to ride bicycles on the roads. Mix and number of haphazard vehicles on the road usually keep the traffic very congested and slow, on most of the roads of Lahore. Nerve Shattering noise and environmental pollution is health hazard for road users. Numbers of steps have been taken by city district Government to promote the sustainability of road transport. The motorcycle rickshaws have been banned on Canal road, Mall road, Jail road and Ferozepur road to combat noise pollution and congestions on these roads (Yasar et al., 2013). Widening of roads, signal freeness of different roads, ban on noisy two stroke motorcycle rickshaws on different selected roads, metro bus project on Ferozepur road and orange line metro train project are some major steps taken by the Government in Lahore. Environmental pollution and congestion on roads has been improved as a result of introduction of overhead bridges & underpasses, road widening and introduction of four stroke rickshaws in the Lahore city. The four stroke rickshaws have been introduced by private sector as a result of ban on two stroke motor cycle rickshaws by the high court. But public has certain reservation on lengthy U-turns, building and business collapse due to road projects, reduced and less accessibility of public transport other than metro bus project, difficulties for pedestrians & bicyclists and consumption of too much money on metro bus and train projects. Much has been done to control the congestion on roads. Underpasses and overhead bridges have been introduced on number of busy crossings. Many roads have been made signal free. A 27 Km long metro bus station has been introduced for public. The traffic congestion has been controlled to much extent on many roads. Orange Line metro train project is under construction. A lot of criticism has been observed from public and opposition parties in terms of lot of budget allocation for a single city by ignoring other small cites and ignoring other facilities like health education and electric power shortage. Numbers of people are migrating from other small cities to Lahore due to lack of facilities in their homelands. City has been expanding at a great rate with introduction of luxurious housing schemes. Very few vertical developments have been introduced in the city. Nothing special has been done to promote bicycle or walk instead cycling and walk has been made more difficult. The roads have become more unsafe for bike riders, cyclists and pedestrians. People have to move to different separate markets to purchase different domestic goods. Despite of number of sustainable steps taken by the Government, many modern tools of sustainability have been overlooked. The brief description of 35 transport sustainability indicators in Table 5.2 shows many overlooked indicators like parking facilities, facilities for cyclists and pedestrians, distance from bus stop, kitchen gardens, fuel quality, use of electronic technologies public participation etc. The transport sustainability index has also been calculated in the Table 5.2. Transport sustainability index of Ferozepur road, Gulberg main boulevard road, Jail road, Mall road and Multan road remained (very low) 47.14, 38.57, 40, 34.29 and 34.29 respectively. None of the Pakistani city has been selected for sustainability index survey, to be able to enlist among (twenty six) cities of Asia and Middle East (De Gruyter et al., 2016). Manila (Philippines), Tokyo (Japan), and Chennai (India) have been ranked on 1st, 2nd, and 3rd positions respectively (De Gruyter et al., 2016).

Table 5.2. Transport sustainability index of different roads

	Sustainability Indicators	Measurement Units	Index Value				
			Ferozepur road	Gulberg Road	Jail road	Mall road	Multan Road
1.	Availability of sidewalks	Sidewalk-miles to route-miles ratio	1	1	1	1	1
2.	Availability of crosswalks	# of Crosswalks /route-mile	1	0.5	1	0.5	0.5
3.	Availability of pedestrian signals	Percentage of signalized intersections	0	0	0	0	0
4.	Availability of ITS pedestrian treatments	Yes/No	0	0	0	0	0
5.	Disability infrastructure	Yes/No	0.5	0	0	0	0
6.	Guide signs	Yes/No	1	1	1	1	0.5
7.	Dedicated bicycle lanes on road	Percentage of network route-miles	0	0	0	0	0
8.	Dedicated bicycle lanes off the road	Yes/No	0	0	0	0	0
9.	Availability of bike sharing services (bike rental)	Yes/No	0	0	0	0	0
10	Bike service stations	Yes/No	1	1	1	1	1
11	Short-haul shuttle/ circulators/ Local bus	Yes/No	1	1	1	1	1
12	Bus rapid access (Metro Bus)	Yes/No	1	0.5	0.5	0.5	0.5
13	Light rail access Commuter rail access	Yes/No	0	0	0	0	0
14	Fast connection with neighbor cities	Yes/No	0.5	0.5	0.5	0.5	0.5
15	Park and ride facilities at rail and bus rapid/bus stations	Yes/No	0	0	0	0	0
16	Suitable headways (30 mins/20min/10 min for rail or local bus or metro bus or shorter)	Yes/No	1	1	1	1	1
17	Dedicated bus lanes	Yes/No	0	0	0	0	0
18	Signal free tracks (presence of overhead bridges and underpasses)	Yes/No	1	1	1	0	0
19	Affordable fair	Yes/No	1	1	1	1	1
20	No of people using Private cars	Number of vehs/household	0	0.5	0	0.5	1
21	Location within ¼ to ½ mile of Public Transport	Yes/No	0.5	0	0	0.5	0
22	Mixed-use buildings	Percentage of buildings with two or more land uses	0.5	0.5	0	0	1
23	Parks/open and green spaces/playgrounds	Percentage of area	1	0	1	0	0
24	Veggie gardens/ kitchen Gardens	Percentage of buildings	0	0	0	0	0
25	Speed control measures - vertical treatments.	Percentage	0.5	0.5	0.5	0.5	0.5
26	Speed control measures - horizontal treatments	Percentage	0	0	0	0	0
27	Volume control measures	Percentage	0.5	0.5	0.5	0.5	0.5
28	E-commerce/E-billing/video	Percentage of household	0.5	0.5	0.5	0.5	0

	conferences	using the service					
29	EIAs (Public Participation)	Yes/No	0	0	0.5	0	0
30	Road width	Relative to other roads and traffic load	1	1	0.5	0.5	1
31	Repair and Maintenance of roads	Public Acceptance	1	1	1	1	0.5
32	Short block lengths (≤ 800 ft.) Streets in a grid pattern	Yes/No	0	0	0	0	0
33	Low power systems /Alternative power systems	Yes/No	0.5	0	0	0	0
34	Use of CNG Buses	Percentage	0.5	0.5	0.5	0.5	0.5
35	Better fuel Quality	Yes/No	0	0	0	0	0
Total			16.5	13.5	14	12	12
Index			47.14	38.57	40.0	34.29	34.29

5.3. Social survey

A social survey has been conducted through a questionnaire. Opinion of 400 people including 96 women and 304 men was taken regarding their mode of transportation, vehicle ownership, hurdles in the use of public transport, factors to promote public transport and their opinion to promote public transport. The questionnaire is attached as Annexure I.

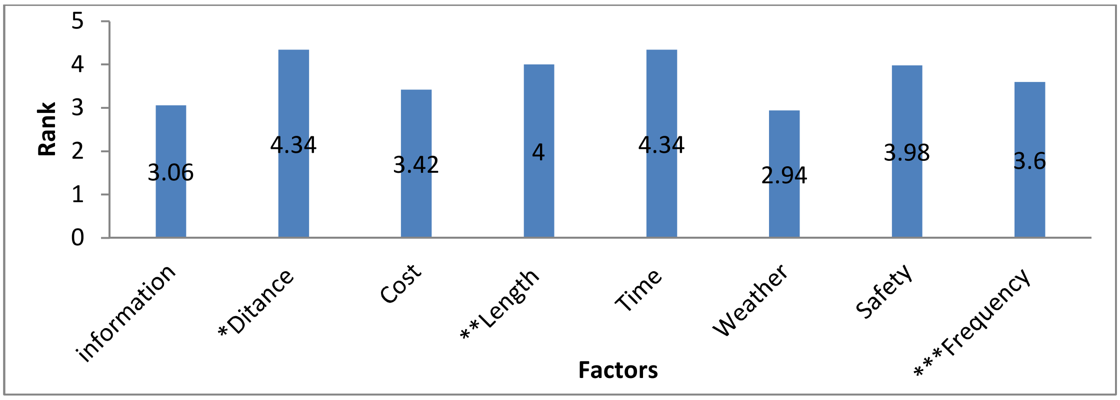
5.3.1. Vehicle ownership and usage

Questionnaire data elaborates that most of the females have no vehicle ownership except 8% have personal cars. Most (92 %) of the females are either given pick & drop service by their family members or otherwise use public transport or taxi for their trips. Around 34 % males have no vehicle ownership, 5% have cars, 55% have motorcycles and 5 % have personal cycles. Overall 48 % people have no vehicle ownership, 6% have cars, 42 % have motorcycles and 4% have cycles. Majority of the people (46 %) use motorcycle, 10 % use car, 2 % use cycle, 14 % use taxi or rickshaw, 16 % use public bus or wagon, 6 % use metro bus and 6 % walk for their trips to university or work place. People were found reluctant to use public transport due to different factors in the survey.

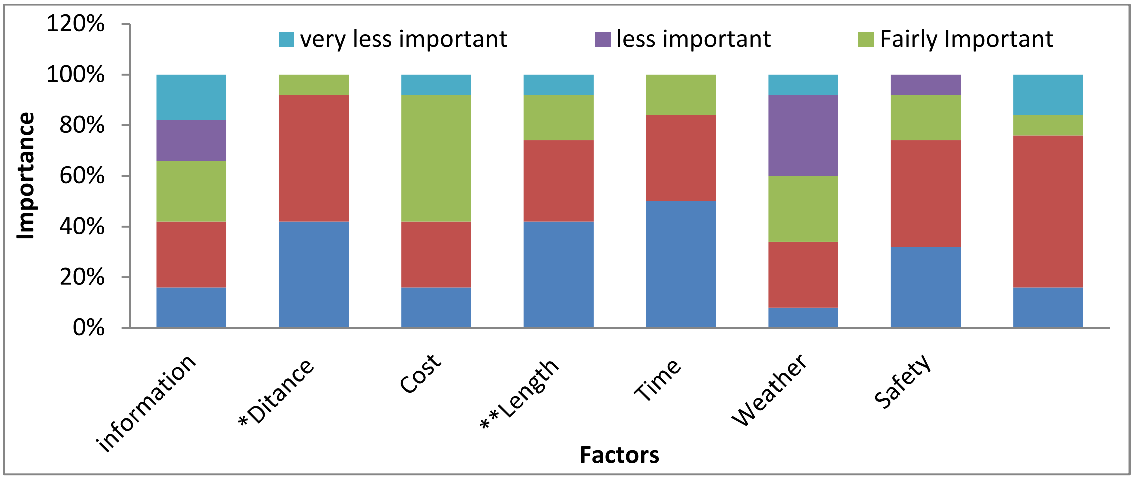
5.3.2. Factors: preventing people from using public transport

"Distance from bus stop" has been declared as very important (5th grade) and important factor (4th grade) by 42 % and 50 % participants respectively, in preventing people from using public transport. As time has been taken as precious resource in the modern world (Stoica et al., 2015). "Total time taken" has been assumed as very important and important factor respectively by 50 % and 34 % people. Frequency of service, safety, length of journey, cost and lack of available information were rated 16 %, 32 %, 42 %, 16 % and 16 % as very effective factors (5th grade) respectively, in preventing people from using public transport. And, frequency of service, safety, length of journey, cost and lack of available information were rated 50 %, 42 %, 32 %, 26 % and 26 % as effective factors (4th grade) respectively, in preventing people from using public transport.

Overall factors are ranked as distance from bus stop, time taken (4.34), length of journey (4), safety (3.98), frequency (3.6), cost (3.42) and information (3.06) respectively, out of 5 grades, in preventing people from using public transport. Factor like weather conditions (2.94) has not been given much importance by the public. Overall importance of the factors (in preventing people from using public transport) is 3.71 out of 5 grades. The detail of factors preventing people from using public transport has been given in Fig. 5.1.a. and Fig. 5.1.b.



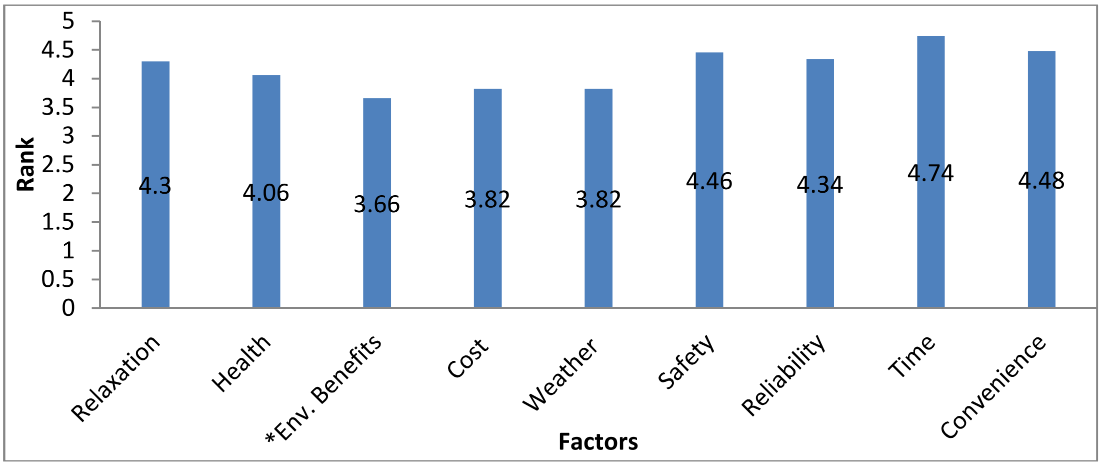
* Distance from bus stop, **Length of Journey, ***Frequency of service
Fig. 5.1.a. Ranking of the factors in preventing people from using public transport



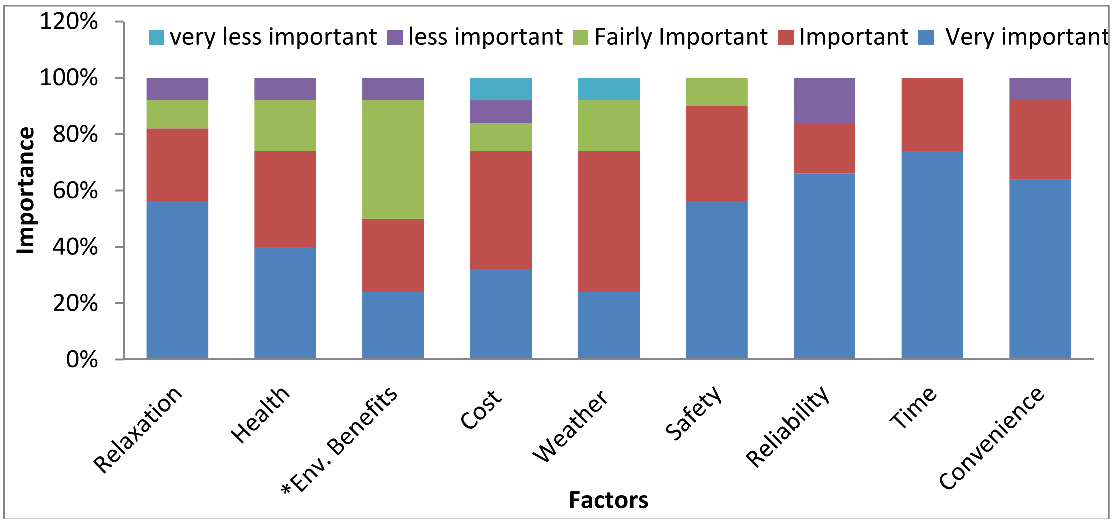
* Distance from bus stop, **Length of Journey, ***Frequency of service
Fig. 5.1.b. Importance of the factors in preventing people from using public transport

5.3.3. Important factors in the choice of transport

People were found very time conscious in their choice of transport. "Time taken" has been rated as very important factor (5th grade) and important factor (4th grade) by 74 % and 24 % people respectively, in their choice of transport. "Convenience" was rated 64 % and 28 % as very important and important factor respectively in the selection of transport. "Route" was rated 74 % and 18 % as very important and important factor respectively in the selection of transport. "Safety", "reliability" and "relaxation" were rated 56 %, 66 % and 56 % respectively as very important (5th grade) and 34 %, 18% and 28 % as important factor (4th grade) respectively, in the choice of transport. "Cost" and "health" has been rated as very important factor in the choice of transport by 42 % and 32 % people respectively. Environmental benefits have been rated as very important factor by 24 % people in the choice of transport. Public wants subsidy in transport sector. It has been found that subsidy for public transport is necessary otherwise quality would be sub-optimal (Nilsson et al., 2016). The survey concludes that time, convenience, route, safety, reliability and relaxation has been taken as the most important factor respectively in the choice of transport. Overall time, convenience, safety, reliability, relaxation, health, cost, weather conditions and environmental benefits were ranked at 4.74, 4.48, 4.46, 4.34, 4.3, 4.06, 3.82, 3.82 and3.66 respectively out of 5 grades, as important factors in the choice of public transport. Overall importance of the factors (in the choice of public transport) is 4.19 out of 5. The detail of importance of factors in the choice of public transport has been given in Fig. 5.2.a. and Fig. 5.2.b.



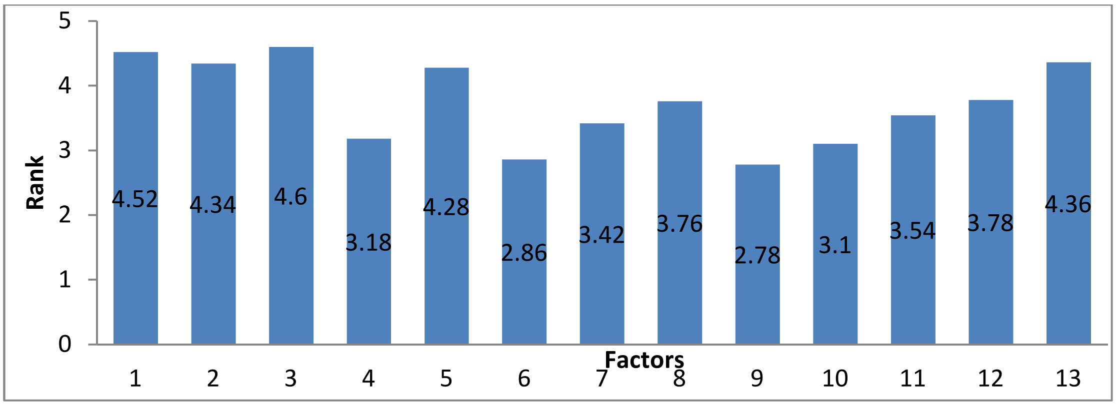
*Environmental benefits
Fig. 5.2.a. Ranking of the factors in choice of public transport



*Environmental benefits
Fig. 5.2.b. Importance of the factors in choice of public transport

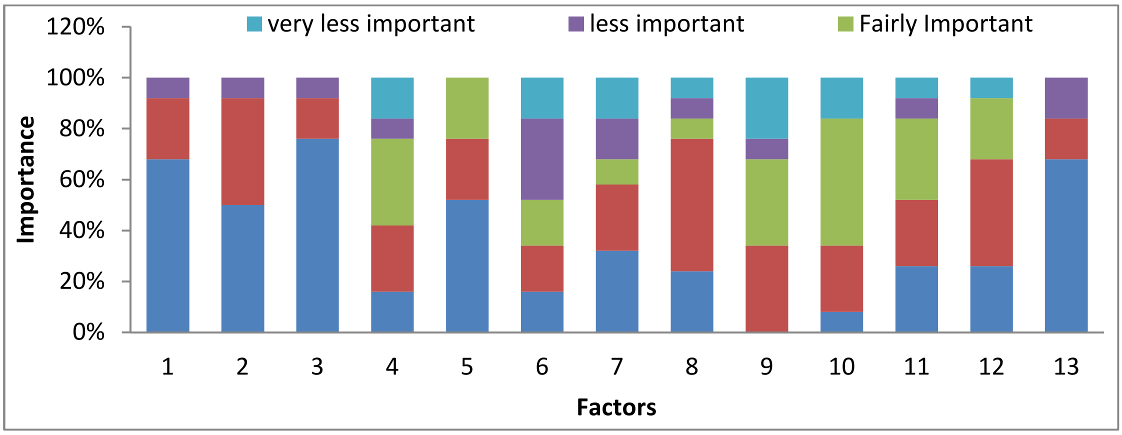
5.3.4. Importance of the initiatives to promote public transport

People were found very conscious in application and implementation of certain initiatives from Government side to improve public transport. “Launch school and work buses”, “more bus routes” and “cheaper fares” were considered as very effective initiative (5^{th} grade) by 68 %, 50 % and 76 % people respectively, to promote public transport. Only 16 %, 16 % and 08 % people declared “less parking space”, “more parking fees” and “onboard entertainment” respectively, as very effective (5^{th} grade) initiative to promote public transport. Majority of the community (76 % people) considered “parking at metro bus stop” as very effective initiative. Similarly, 68 % people talk about provision of more reliable bus service as very effective initiative. Only 26 % people were interested in separate cycle lanes and 26 % considered cycle & pedestrians u turn bridges as very effective initiative. Overall factors are ranked as: cheaper fares (4.6), availability of school/work bus, more reliable service (4.36), more bus routes (4.34), extended bus service (4.28), cycle pedestrian u-turn bridges (3.78), parking availability at metro bus stop (3.76), cycle lanes (3.54), free cycle parking (3.42), less parking space for vehicles (3.18), onboard entertainment (3.1), higher parking fees (2.86), car sharing scheme (2.78) respectively out of 5 grades, as important initiatives to promote public transport. The overall importance of the initiatives (to promote public transport) is 3.73 out of 5 grades. People during their interviews emphasize to stop migration to Lahore, through provision of health, education, employment, industrial and fast transport facilities in other cities and remote areas as well. Some people emphasize to provide economical, better and accessible public transport for all the housing societies of Lahore, to promote the use of public transport and to lessen the use of private vehicles, especially cars. The detail of effectiveness of the initiatives to promote the public transport/ transport sustainability has been given in Fig. 5.3.a. and Fig. 5.3.b.



1: School/Work Bus, 2:More bus routes, 3: Cheaper fares, 4: Less parking space, 5: Extended bus service, 6: Higher parking fees, 7: Free cycle parking, 8: Parking at metro bus stop, 9: Car sharing scheme, 10: On board entertainment, 11: Separate cycle lanes, 12: Cycle pedestrian U turns, 13: More reliable service

Fig. 5.3.a. Ranking of the initiatives to promote transport sustainability

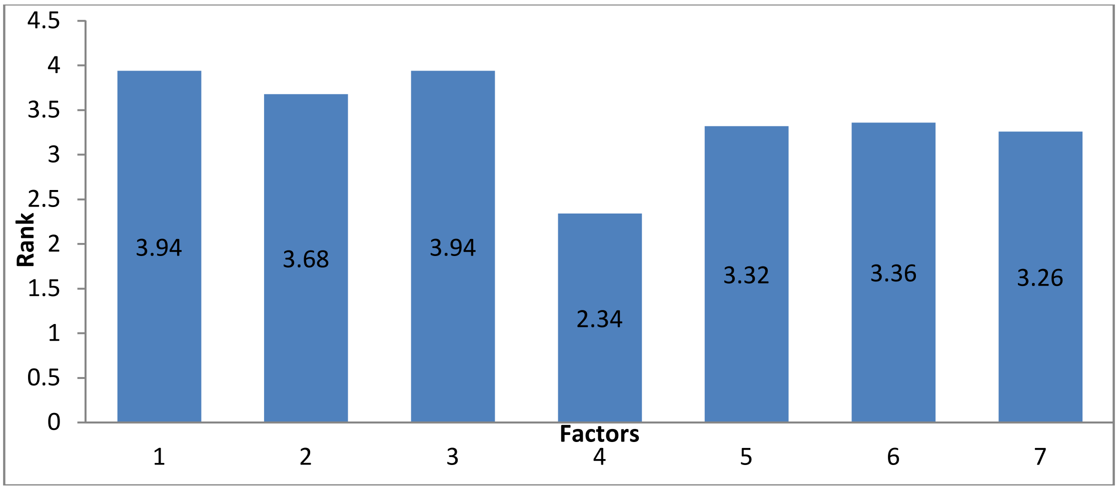


1: School/Work Bus, 2: More bus routes, 3: Cheaper fares, 4: Less parking space, 5: Extended bus service, 6: Higher parking fees, 7: Free cycle parking, 8: Parking at metro bus stop, 9: Car sharing scheme, 10: On board entertainment, 11: Separate cycle lanes, 12: Cycle pedestrian U turns, 13: More reliable service

Fig. 5.3.b. Effectiveness of the initiatives to promote transport sustainability

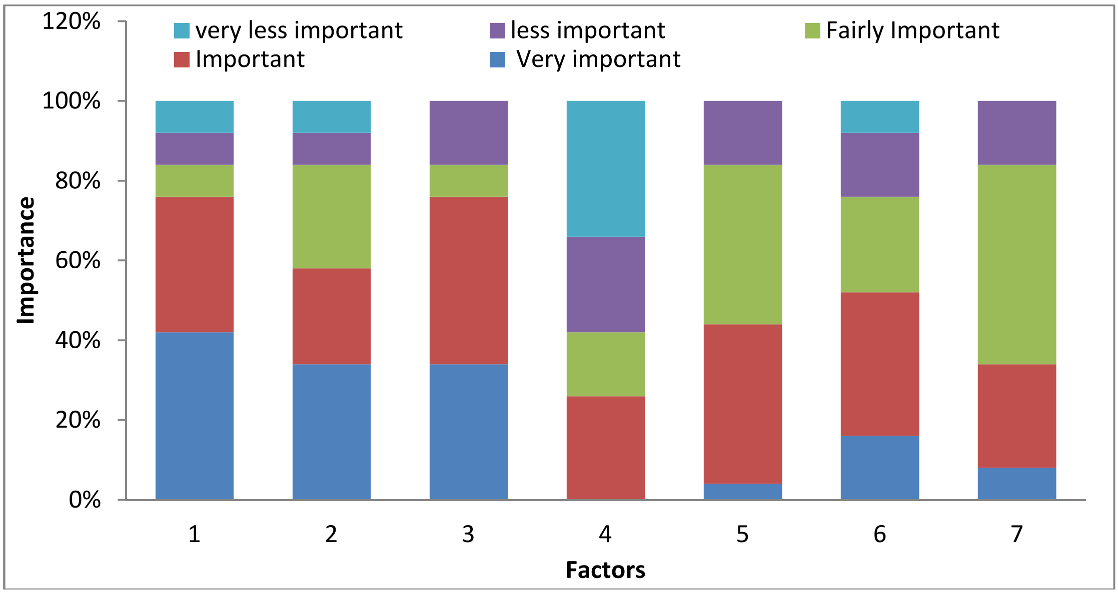
5.3.5. Effectiveness of the advertisement techniques

The concept of transport sustainability was new for most of the stake holders. Even the people were not found so much interested in the advertisement of transport sustainability. Only 34 % people considered television and 34 % people considered poster advertisement as very effective tool (5^{th} grade) to promote transport sustainability. Similarly, only 34 % and 16 % people considered leaflets and radio advertisement respectively as very effective tool. Billboards, text messages, social media and advertisement in buses were considered as very effective tool (5^{th} grade) by 04 %, 20 %, 22 % and 34 % respectively, to promote public transport. Overall advertisement techniques are ranked as: posters, television advertisement (3.94), leaflets (3.68), radio advertisement (3.36), hoardings/billboards (3.32), advertisement in buses (3.26), emailed advertisement (2.34) respectively out of 5 grades. Overall the importance of the advertisement techniques is 3.41 out of 5 grades. The detail of the effectiveness of the advertisement methods to promote transport sustainability has been given in Fig. 5.4.a. and Fig. 5.4.b.



1: Posters, 2: Leaflets, 3: Television advertisement, 4: Emailed advertisement,

5: Hoardings/Billboards, 6: Radio Advertisement, 7: Advertisement in buses
Fig. 5.4.a. Ranking of the advertisement methods to promote transport sustainability



1: Posters, 2: Leaflets, 3: Television advertisement, 4: Emailed advertisement, 5: Hoardings/Billboards, 6: Radio Advertisement, 7: Advertisement in buses
Fig. 5.4.b. Effectiveness of the advertisement methods to promote transport sustainability

5.4. Summary

As a developing country, lots of gaps and weaknesses have been found in urban planning of Lahore, Pakistan at policy level. One of the main factors is emerging population of the city, due to migration of people from Punjab province for jobs & education and from other provinces due to security reasons. Another main factor is lack of basic facilities at grass root level, which compel people to migrate to Lahore. In this study, the main indicators of transport sustainability: shifting of modes from private to public vehicles, land use planning and sustainable operations have been studied. Transport sustainability index of Ferozepur road, Gulberg main boulevard road, Jail road, Mall road and Multan road remained 47.14, 38.57, 40, 34.29 and 34.29 respectively. Lack of parking space at most of the roads has made the roads congested for traffic. Although cars are usually around 10 % of traffic load, still this quantity is sufficient to congest the roads of Lahore. The new colonies mostly have no or very less provision of public transport facility at 10 to 15-minute walk from homes. People do not want to use public transport. The public transport users are mostly from lower middle class and poor communities. Communities near metro bus project have problems to cross the road as well as to meet their clients. The land use developments have lots of weaknesses and gaps, forcing people to use private transportation.

Development in road infrastructure with lengthy U-turns, underpasses and overhead bridges, has been made for car users only, and has ignored the poor communities, pedestrians and cycle users. It is very difficult to walk along the road or cross the road for pedestrians. Lengthy U-turns have forced the people to violate one-way traffic rules. Auto rickshaw drivers, motorcycle users and cyclist may not be considered safe during one-way violations and during lane change for turns.

More than 80 % stake holders pointed out distance from bus stop, much time taken, lack of available information and low frequency of bus service as major cause of preventing public from using public transport. Distance from bus stop, time taken and length of journey were ranked ≥ 4 out of 5 grades in the survey. Time, convenience, safety, reliability, relaxation and health were ranked above 4 out of 5 grades in the choice of public transport, during survey. Cheaper fares, availability of school/work bus, more reliable service, more bus routes and extended bus service were ranked (above 4 grades), as important factors to promote public transport. None of the advertisement technique was ranked above 4 to promote public transport.

RESULTS AND DISCUSSION
AIR QUALITY MODELING

CHAPTER 6

6. Air quality modeling

The objective of this chapter is to find out emission factor of different classes of vehicles as well as to model the certain air pollutants level in five different main streets of Lahore, Pakistan. The percentage of different classes of vehicles on different streets has been calculated. The background urban emissions data has been taken from air quality monitoring station installed at Town Hall building at Mall road. The air pollutants level has been modeled with the help of Operational Street Pollution Model (OSPM). The data of street configuration, background urban air pollution, meteorological conditions, diurnal traffic count and emission factor of vehicles has been made available to model the pollutants level at different streets. In the end a correlation between observed and modeled results has been calculated.

6.1. Street air pollution modeling

The 24-hourvehicular traffic data of five busy streets (Ferozepur road, Gulberg main boulevard road, Jail road, Mall road and Multan road) has been taken. The 24-hourair pollution (NOx, CO, O_3, SO_2 and $PM_{2.5}$) and meteorological data (wind speed, wind direction, solar radiations, temperature and relative humidity) of the above said five roads has been taken through Horiba air quality monitoring instruments. Air pollution level has been modeled through OSPM model by inputting traffic data, emission factor of different vehicles, street configuration and metrological data. The locations of five selected streets, Ferozepur road, Gulberg main boulevard road, Jail road, Mall road and Multan road have been shown in Fig. 6.1.a., Fig. 6.1.b., Fig. 6.1.c., Fig. 6.1.d., and Fig. 6.1.e. respectively.

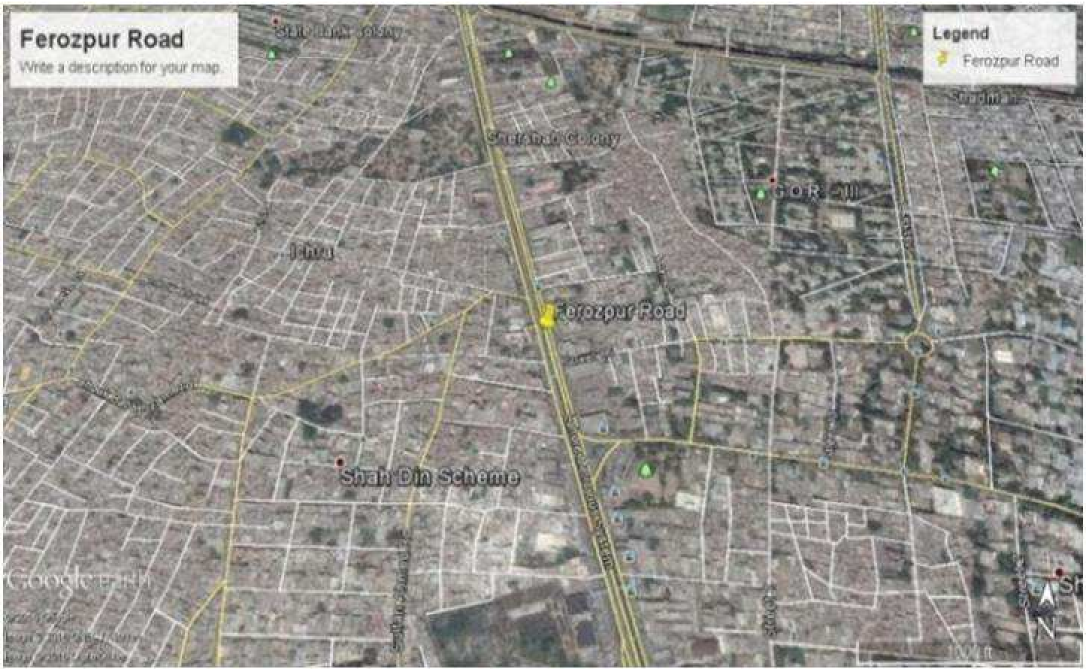


Fig. 6.1.a. A view of Ferozepur road

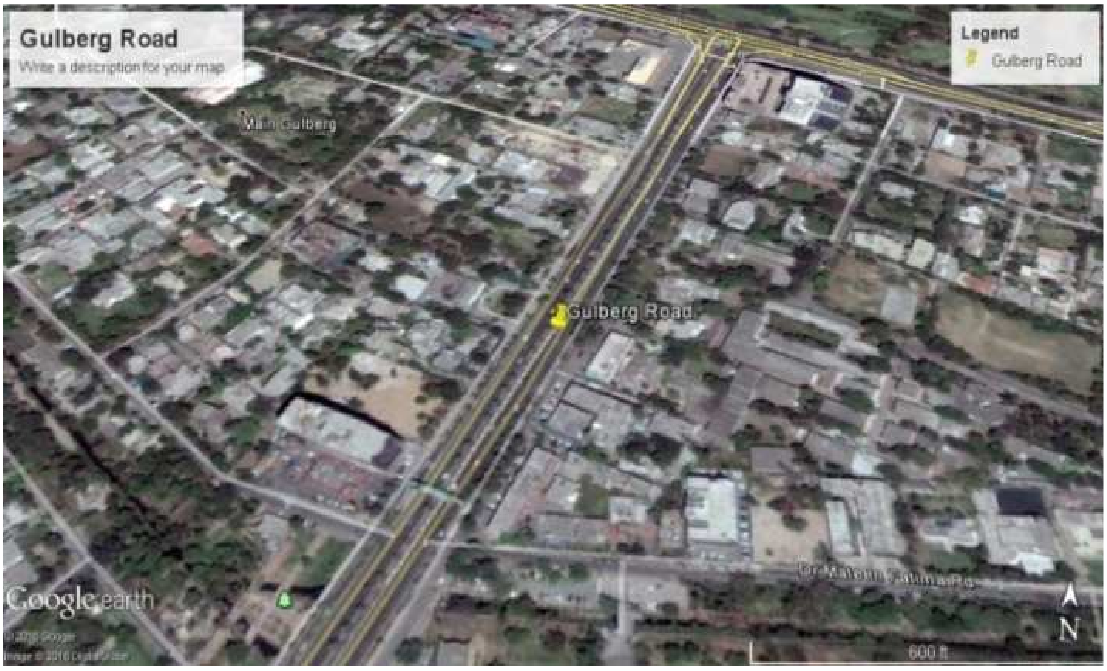


Fig. 6.1.b. A view of Gulberg road

Fig. 6.1.c. A view of Jail road

Fig. 6.1.d. A view of Mall road

Fig. 6.1.e. Google location of Multan road

6.2. Street configuration

In the current study five main streets (roads) of Lahore have been selected for air pollution modeling. Operational Street Pollution Model (OSPM) software has been chosen for the modeling of air pollutants. Plume (Gaussian) and box model have been combined in the OSPM Model. The Gaussian part calculates the concentration of emitted pollutants and the box model deals with the parts of pollutants in the street. The OSPM software requires data like street configuration, background emissions & meteorological data, diurnal vehicle data, average speed of vehicles and emission factor of vehicles. In the first step the configuration of streets has been calculated. The street configuration includes road width, building height and street axis orientation. More over the 24-hour data of different vehicle classes and average speed of vehicles has been calculated. The locations of air quality monitoring station and five selected streets have been shown in Fig. 6.2.

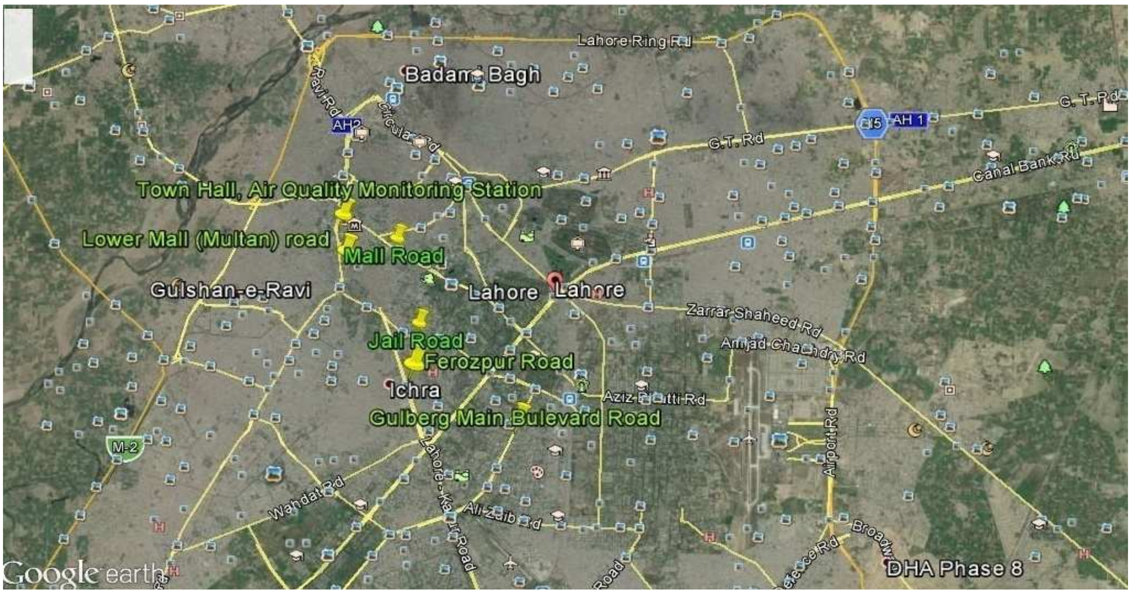


Fig. 6.2. Study area (location of streets and air quality monitoring station)

The street configuration of five different streets has been given in Table 6.1.

Table 6.1. Street configuration and average speed of vehicles

No.	Street Name	Building Height (m)		Average Street Width (m)	Orientation	Average Speed of vehicles (Km)
		Side 1	Side 2			
1.	Ferozepur Road	10	08	40	108°	35-40
2.	Gulberg Road	15	12	60	63°	50
3.	Jail Road	10	8	45	143°	50
4.	Mall Road	8	7	35	148°	35-40
5.	Multan Road	8	4	35	100°	40

6.3. Diurnal Traffic Count

It has been studied that motorcycles are the dominant vehicle class in the streets of Lahore. Cars (cars, jeeps and pickups) comprise second big category. As an average of five streets motorcycles, cars, auto-rickshaws, vans, minibuses trucks and buses are 53%, 31%, 10%, 3%, 2%, 0.63% and 0.31% respectively of overall vehicles as shown in Fig. 6.3.f. The percentage of motorcycle varies from 48 % at Jail road to 58% at Multan road. The percentage of cars varies from 26% at Multan road to 37% at Jail road as shown in Fig. 6.3.

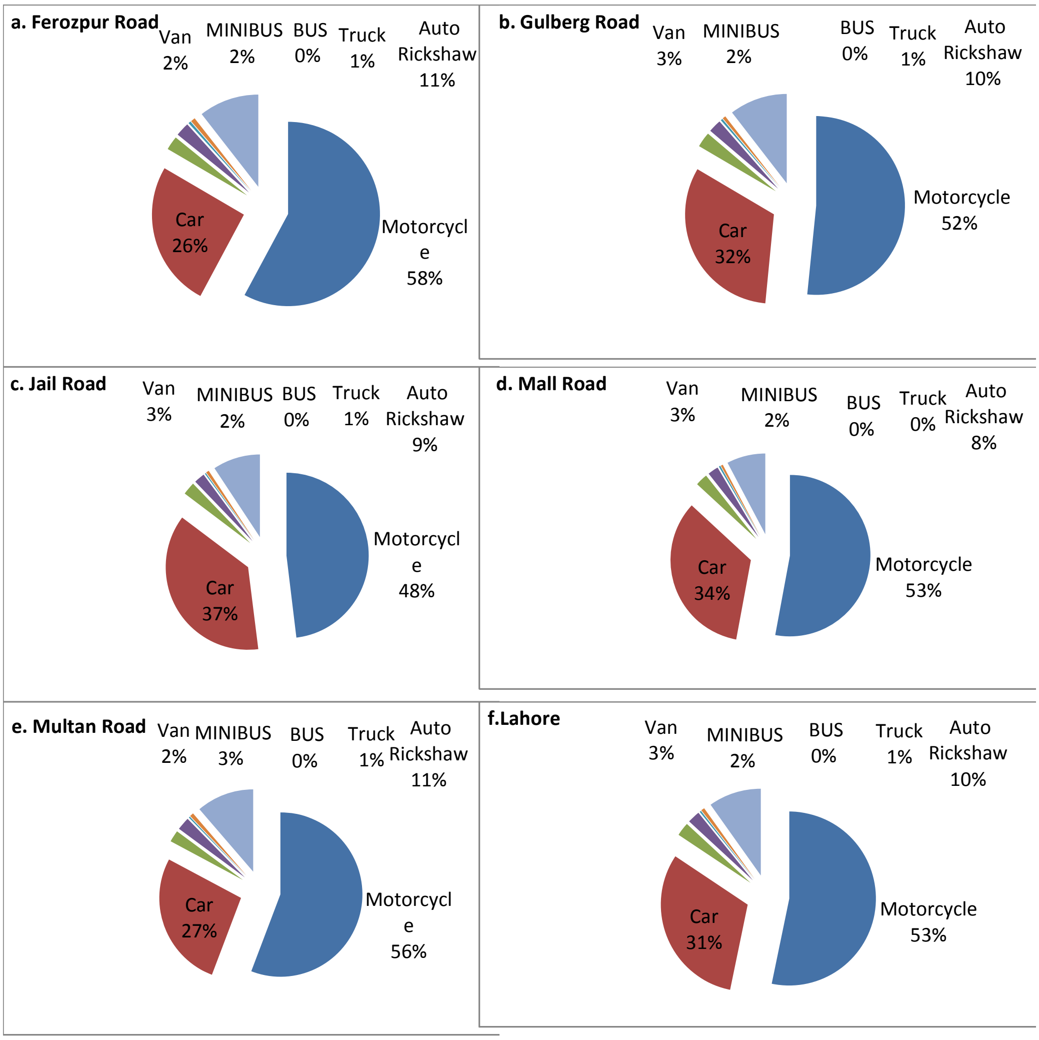


Fig. 6.3. Percentage of vehicles at different streets of Lahore

6.4. Calculation of emission factors

The emission factors of different vehicles have been calculated with the help of OSPM software. The emission factor for PM_{10}, $PM_{2.5}$, NOx, Benzene and CO have been calculated through OSPM by taking into account the fuel characteristics of 1990 levels and vehicles of year 2000 level, used in Europe for an average speed of 40 Km. The emission factor of SO_2 have been taken from a study in Vietnam, due to similar conditions (Hung, 2010). The emission factor of gasoline auto rickshaw are considered equivalent to car due to similarity of their emissions level as prescribed by

Yasar (Yasar et al., 2013). The emission factors of seven different vehicles are given in Table 6.2.

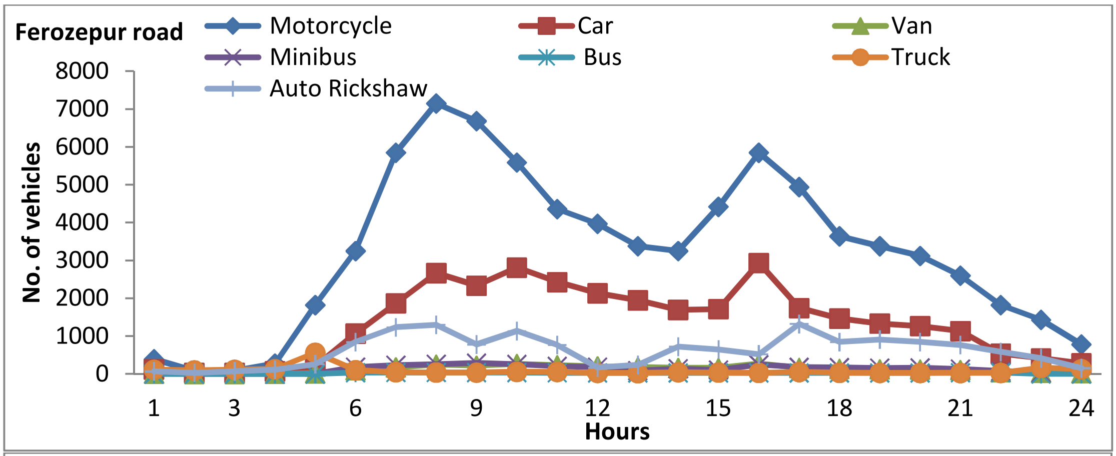
Vehicle Class	Emission Factor (g/Km)					
	$PM_{2.5}$	PM_{10}	SO_2	NOx	CO	Benzene
Motorcycle	--	0.10	0.03	0.30	3.62	0.02
Car	0.015	0.05	0.17	0.98	7.80	0.23
Van	0.022	0.07	0.25	1.52	3.00	0.07
Minibus	0.062	0.23	0.25	6.45	2.59	0.05
Bus	0.062	0.23	0.64	9.66	2.52	0.03
Truck	0.081	0.25	0.40	12.52	2.19	0.03
Auto Rickshaw	0.015	0.05	0.17	0.98	7.80	0.23

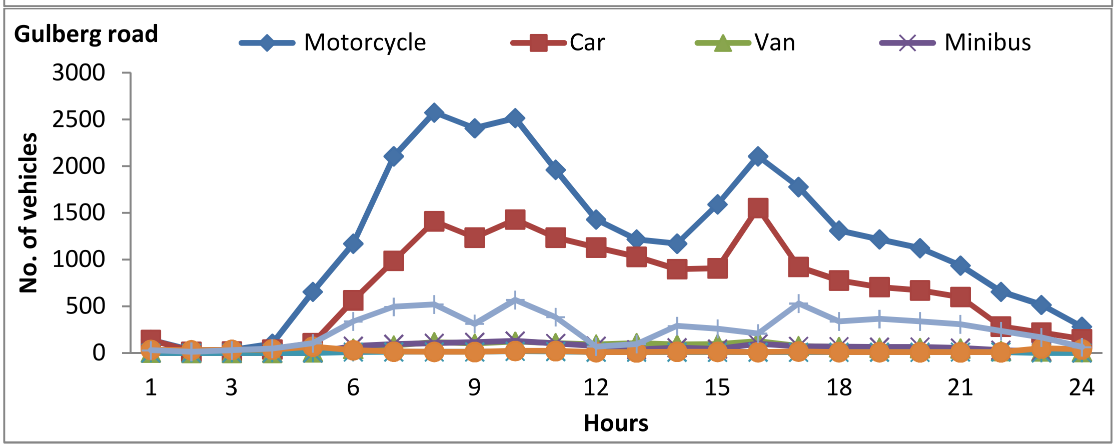
6.5. Diurnal traffic pattern

The diurnal pattern of traffic has been shown in Fig. 6.4. The diurnal total traffic count of different vehicles has been given in Table 6.3. The diurnal pattern of traffic is almost same at all the roads of Lahore. Usually, 7-8 am is starting time for schools, colleges and Government offices. Banks and private offices follows 9 am to 5 pm schedule. The business hubs and shopkeepers usually attend their offices at 10-11 am. Therefore, 8-10 am are usually peak hours in the morning. Schools off time are usually 1 pm to 2 pm, which lead to congestion on roads, around 1-2 pm. The off time from Government offices is usually 3-4 pm. So the second highest peak has been observed from 1-3 pm. The business hubs and shopkeepers usually wind-up their tasks from 7-10 pm, which lead to traffic load at 6-8 pm on roads as third peak. The heavy traffic is allowed from 11 pm to 6 am in the main city, which results in enhanced diesel fuel related pollutants (SO_2 and NOx) at 11 pm to 1 am (can be seen in Fig. 4.1). The buses traffic remains almost nil from 11 pm to 6 am.

Table 6.3. Average diurnal traffic count for each vehicle class on five selected streets of Lahore

Street Name	Motorcycle	Car	Van	Minibus	Bus	Truck	Auto Rickshaw
Ferozepur road	59213	26169	24689	2432	440	802	10830
Gulberg road	22212	13740	1185	1019	146	249	4522
Jail road	24642	19101	1288	1081	119	309	4765
Mall road	32084	20531	1506	1325	190	259	4703
Multan road	40994	19776	1709	1871	186	547	8331





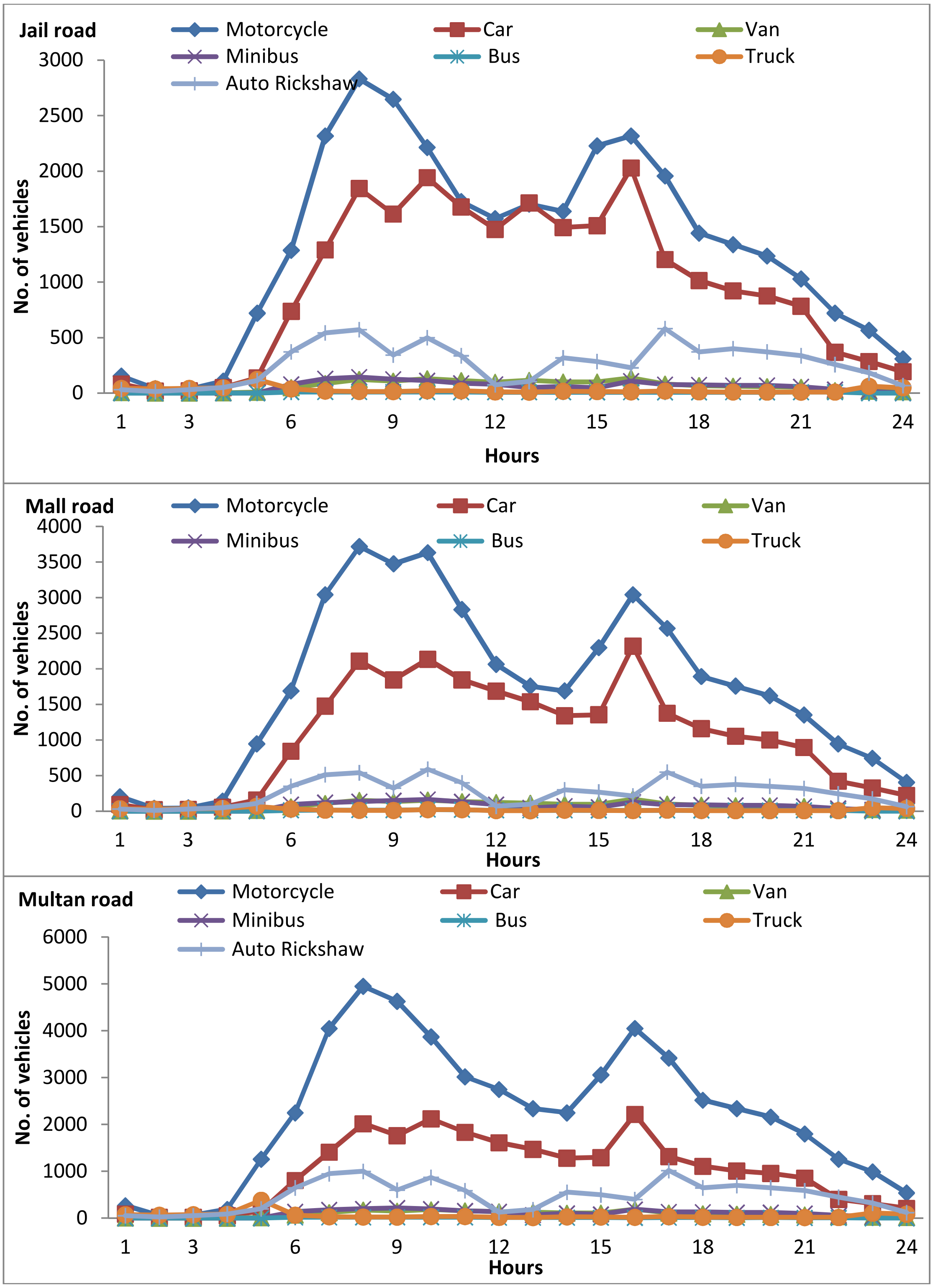


Fig. 6.4. Diurnal traffic pattern at five different streets of Lahore

6.6. Evaluation of modeled results

The comparison of observed, modeled and background results have been shown in Figs. 6.5, 6.6, 6.7, 6.8 and 6.9 for Ferozepur road, Gulberg road, Jail road, Mall road and Multan road respectively. The correlation between modeled and observed data has been given in Table 6.5. The background station has been installed at second floor of Town Hall building at Mall road, which is a polluted area of Lahore. The observed results on different streets are higher than background results except for some duration at Jail road and Gulberg road. This is might be due to high width and low building heights of Jail road and Gulberg road. The modeled data of NOx is slightly higher at day times but quite consistent at night for all the observed points. The modeled concentration of CO has strong correlation between observed and modeled data for Gulberg (r-value = 0.72) and Jail road (r-value = 0.66). For Mall and Multan road, concentration of modeled CO is slightly higher at day time. The observed concentration of CO at Ferozepur road (r-value = 0.53) is much fluctuating, may be due congestion, high building height and enhanced inversion due to metro-bus bridge in between the road. The sudden shoot in CO levels may also be observed due to use of petrol generators by small shopkeepers, during electric power shortage hours. The modeled concentration of SO_2 has strong correlation with the observed results; but the results are different for different streets. The modeled concentration of SO_2 at Ferozepur road and Multan road is slightly low from 10-12 pm and at slightly high at night. At Gulberg road, modeled concentration is much higher than observed from 1 am to 10 am. Overall modeled SO_2 data has significant correlation with the observed data. Modeled SO_2 has significant correlation with minimum r-value = 0.57 for Multan road and maximum r-value = 0.92 for Mall road. Modeled NOx has minimum correlation (r-value = 0.42) at Gulberg road and maximum correlation at Mall road (r-value = 0.92). Modeled CO has minimum correlation at Ferozepur road (r-value = 0.53) and maximum correlation at Mall road (r-value = 0.88). The modeling results have shown much correlation with observed results, as did by many previous studies in Stockholm, Helsinky, Copenhagon, China, USA, Vietnam and India by using OSPM (Fu et al., 2000; Ziv et al., 2002; Aquilina and Micallef, 2004; Mensink et al., 2006; Vardoulakis et al., 2007; Berkowicz et al., 2008; Jensen et al., 2009; Hung, 2010; Kumar et al., 2016).

The background data of $PM_{2.5}$ is available, but not modeled due to much contribution of $PM_{2.5}$ and PM_{10} from sources other than vehicles in Lahore. For example, the construction work for orange line metro train project has enhanced the PM level in the city to much high extent. Overall the modeled results are quite useful, and have strong correlation and resemblance with the observed results as shown in Table 6.4.

Table 6.4. Correlation of modeled results with observed results at different streets of Lahore

No.	Street Name	Pollutant Name	Pearson Correlation (r-value)
1.	Ferozepur Road	SO_2	0.63
		NOx	0.68
		CO	0.53
2.	Gulberg Road	SO_2	0.66
		NOx	0.42
		CO	0.72
3.	Jail Road	SO_2	0.80
		NOx	0.66
		CO	0.66
4.	Mall Road	SO_2	0.92
		NOx	0.92
		CO	0.88
5.	Multan Road	SO_2	0.57
		NOx	0.73
		CO	0.67

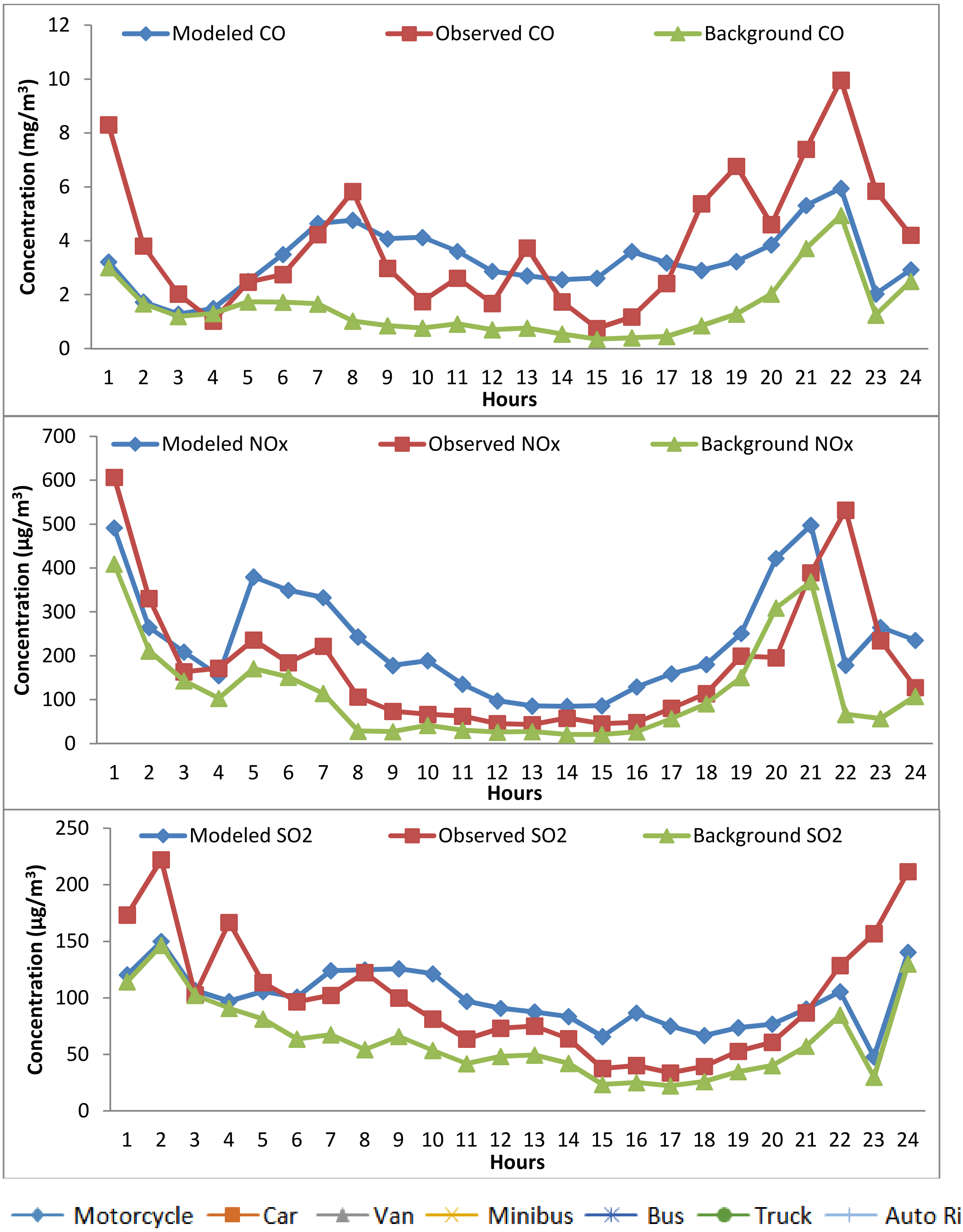


Fig. 6.5. Comparison of observed, modeled and background pollutants levels at Ferozepur road

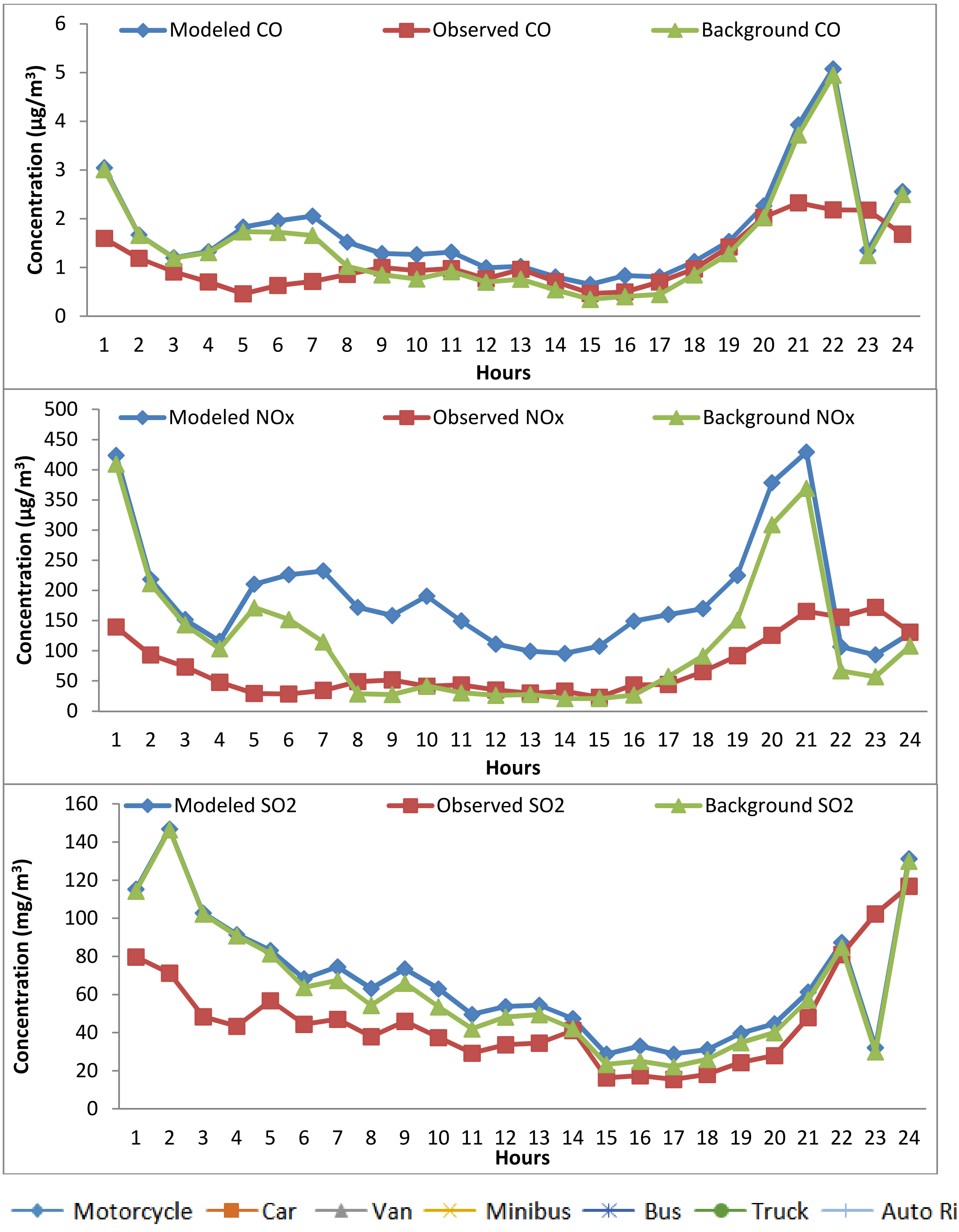


Fig. 6.6. Comparison of observed, modeled and background pollutant levels at Gulberg road

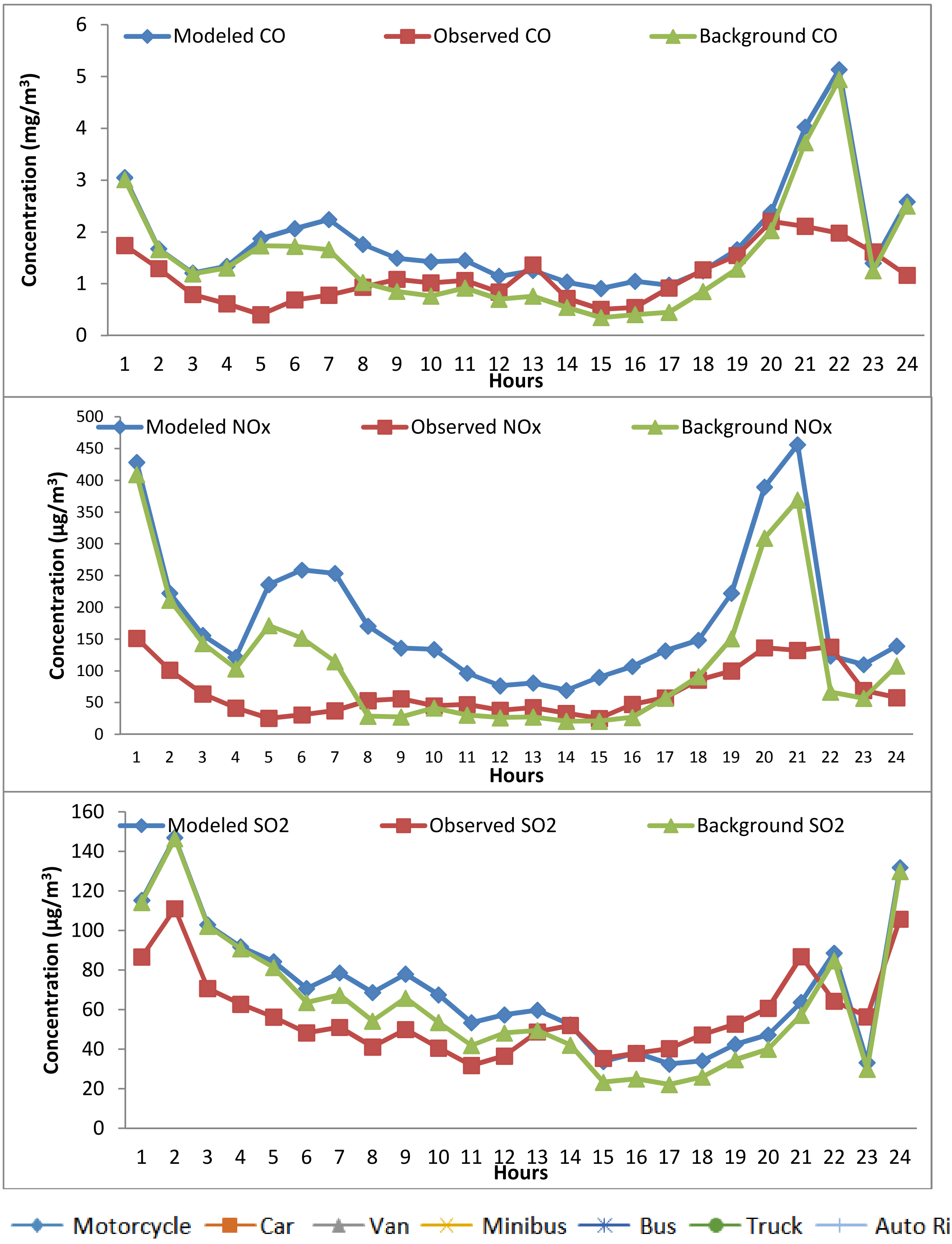


Fig. 6.7. Comparison of observed, modeled and background pollutants levels at Jail road

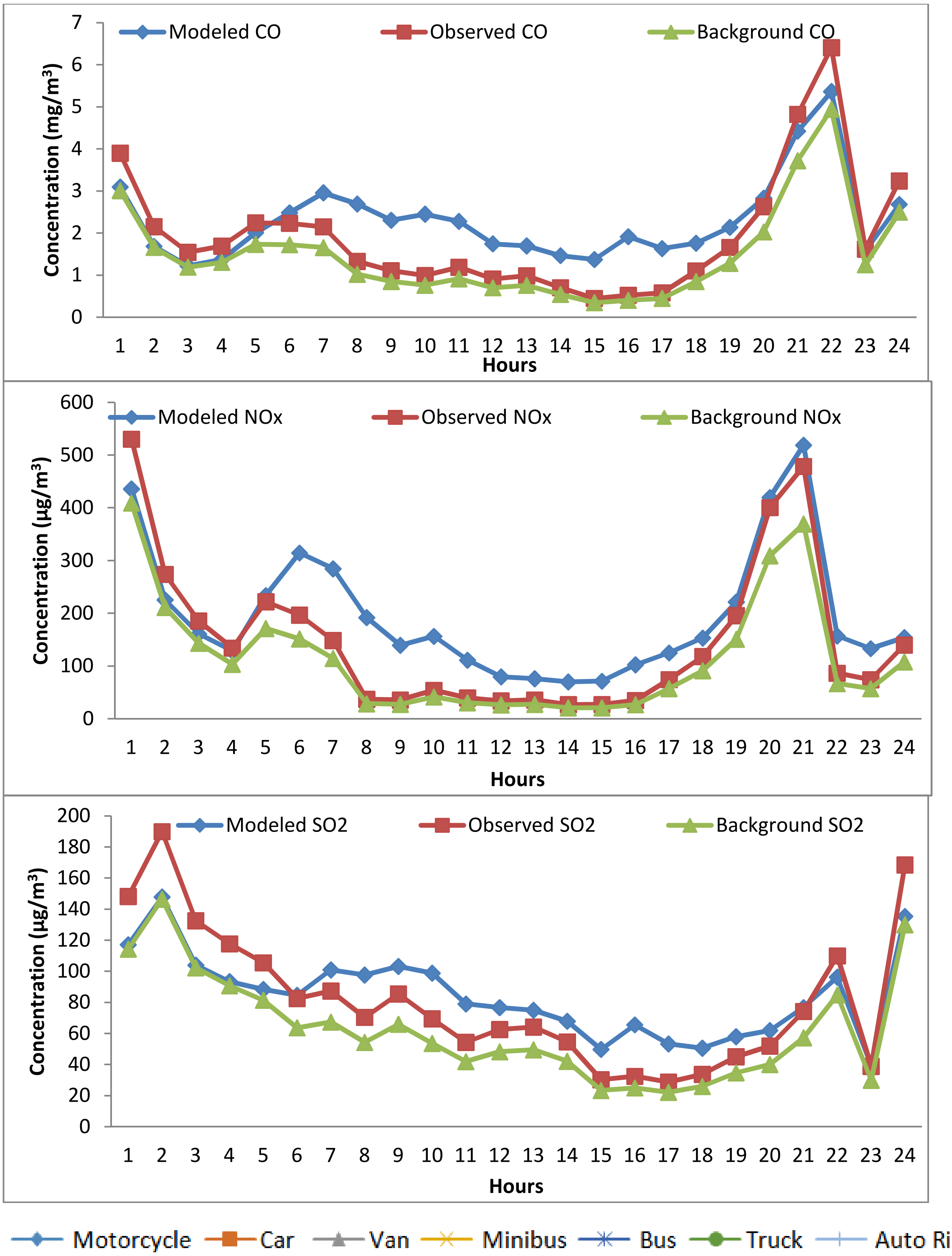


Fig. 6.8. Comparison of observed, modeled and background pollutants levels at Mall road

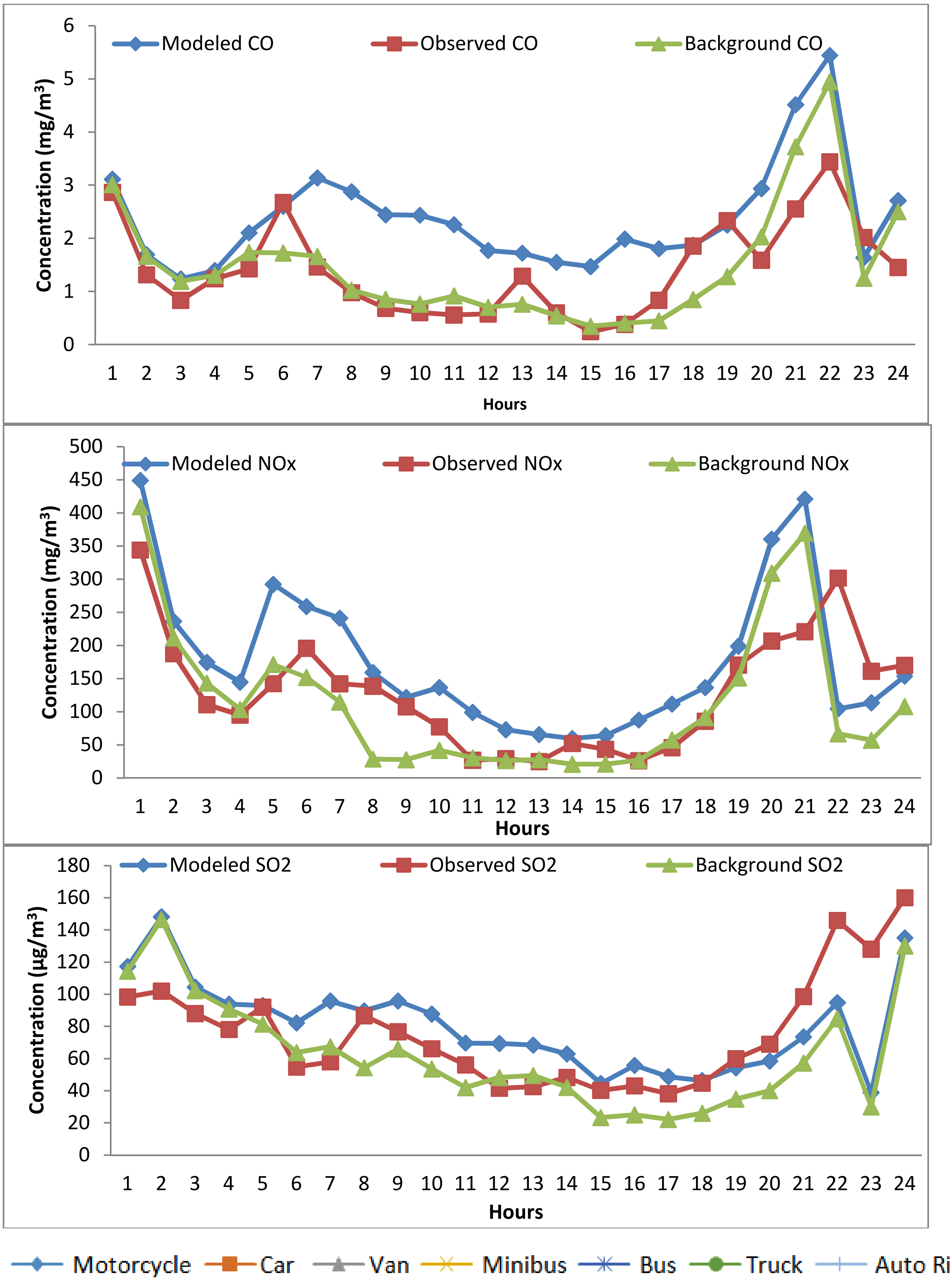


Fig. 6.9. Comparison of observed, modeled and background pollutants levels at Multan road

6.7. Summary

Motorcycles are the main feature of traffic in Lahore due to their low buying and operational cost. Motorcycles comprise around 53 % of overall traffic in Lahore. Cars and auto rickshaws comprise 31 % and 10 % respectively of overall traffic count. People are found reluctant to use public transport. No significant peak hours of traffic have been observed due to difference in timings of schools, Government offices, private offices and commercial markets. Peak hours have been observed from 8-10 am, 1-3 pm and 6-8 pm on almost all the streets. The percentage of different vehicles at all selected streets is almost same, except little high percentage of cars at Gulberg and Jail road. The emission factors of seven classes of vehicles have been calculated through OSPM, according to their fuel quality, engine type and average speed. In the next step the air pollution has been modeled with the help of OSPM. The data of street configuration, diurnal traffic count, average speed, meteorological conditions and back ground urban emissions level has been used as input data to model air pollution at five different streets of Lahore. The modeled results have shown significant correlation (r-value > 0.5) with observed results. The background pollution level is always less than the road pollution level. But as the background air quality monitoring station at Town Hall building at Mall road, has been installed in commercial area, the modeled results for relatively clean areas like Gulberg road may show less correlation. The better modeling results have been observed for those streets which are relatively polluted and are close to the background urban air quality monitoring station. For the Mall road for example, the r-value for SO_2, NOx and CO is 0.92, 0.92 and 0.88 respectively.

RESULTS AND DISCUSSION
TRANSPORT SUSTAINABILITY AND AIR QUALITY

CHAPTER 7

7. Transport sustainability and air quality

Transport sustainability has direct association with improvement of urban emissions level. Promotion of public transport, walk and bicycle and reduction of personal cars can definitely decrease the emissions levels in the city. Similarly, other steps like provision of facilities at grass root level, improvement in vehicle & fuel quality, use of internet communication and land use reforms can definitely improve the urban air quality in the city.

7.1. Impact of reduction in number of personal cars

There are high number of personal cars on the road due to no or very less use of public transport by the upper and middle class of the city. The use of personal cars can be reduced to a considerable number through introduction of better and efficient public transport for the public. The detail of average total number of cars travelled on five different roads has been given in Fig. 7.1. A calculated emission level at five different roads due to cars has been given in Table 7.1. The decrease in number of cars on roads can definitely reduce the emission levels on roads. A possible decrease in emission levels with decrease in number of cars and improvement in speed has also been described in Table 7.1.

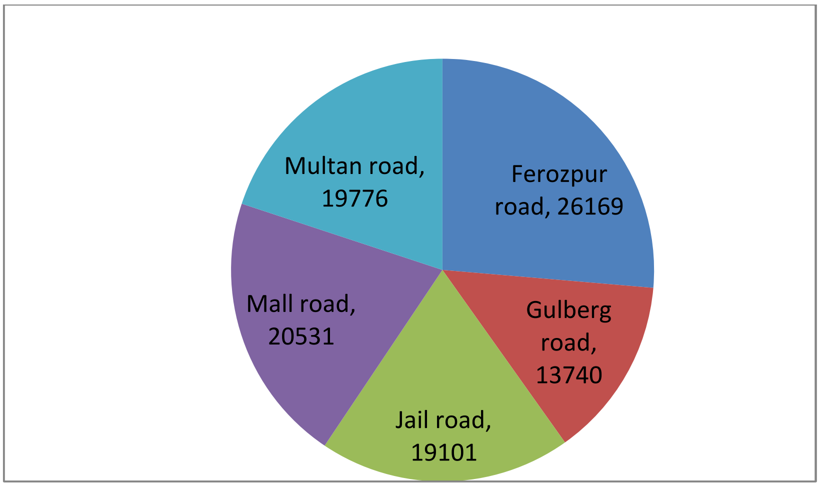


Fig. 7.1. Number of travelling cars on five different roads, during 24 hours

PM_{10} and SO_2 emission factors remain almost same with gain in speed of vehicles (from 40 to 50 Km/hr). An estimated decrease of 7% of NOx emissions, 33% of CO emissions and 25.8% benzene have been observed with 10 % reduction in number of cars and 10 Km/hr gain in speed (from 40 to 50 Km/hr). Similarly, 17.5%, 40.7 and 34% decrease has been observed in NOx, CO and benzene emissions respectively with 20% decrease in number of cars and 10 Km/hr gain in speed (from 40 to 50 Km/hr), as can be accessed from Table 7.1.

Table 7.1. Possible decrease in car emissions level on five different roads

	Street Name	Emissions kg/ km				
		PM_{10}	SO_2	NOx	CO	Benzene
Emissions generated by Cars per each Km at average speed of 40 Km/hr	Ferozepur road	2.617	4.449	25.646	204.093	6.124
	Gulberg road	1.374	2.336	13.465	107.159	3.215
	Jail road	1.910	3.247	18.719	148.971	4.470
	Mall road	2.053	3.490	20.121	160.123	4.804
	Multan road	1.978	3.362	19.381	154.241	4.628
With 10% decrease in number of cars and gain in speed (at 50 Km/hr)	Ferozepur road	2.355	4.004	23.811	136.250	4.546
	Gulberg road	1.237	2.102	12.502	71.538	2.387
	Jail road	1.719	2.923	17.380	99.451	3.318
	Mall road	1.848	3.141	18.681	106.896	3.566
	Multan road	1.780	3.026	17.995	102.969	3.435
With 20% decrease in number of cars and gain in speed (at 50 Km/hr)	Ferozepur road	2.094	3.559	21.166	121.111	4.041
	Gulberg road	1.099	1.869	11.113	63.589	2.121
	Jail road	1.528	2.598	15.449	88.401	2.949
	Mall road	1.642	2.792	16.606	95.019	3.170
	Multan road	1.582	2.690	15.996	91.528	3.054

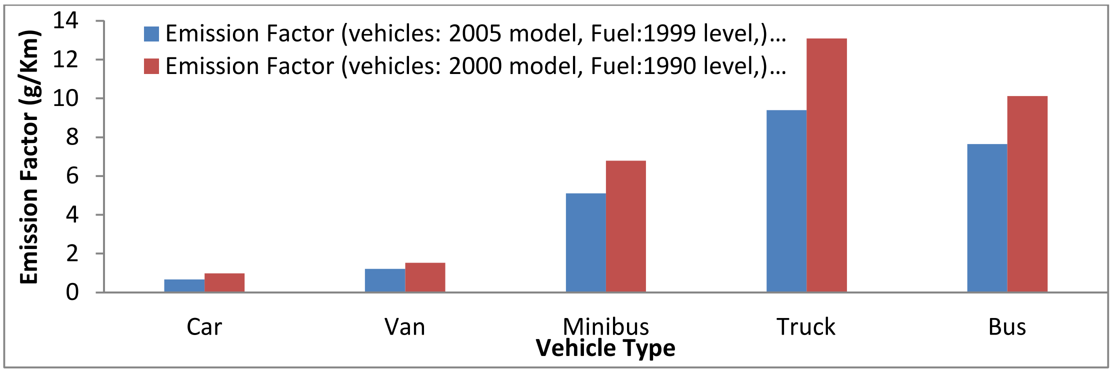
The questionnaire survey depicts that road users wants less number of cars on the road. People are happy with improvement of speed on signal free tracks.

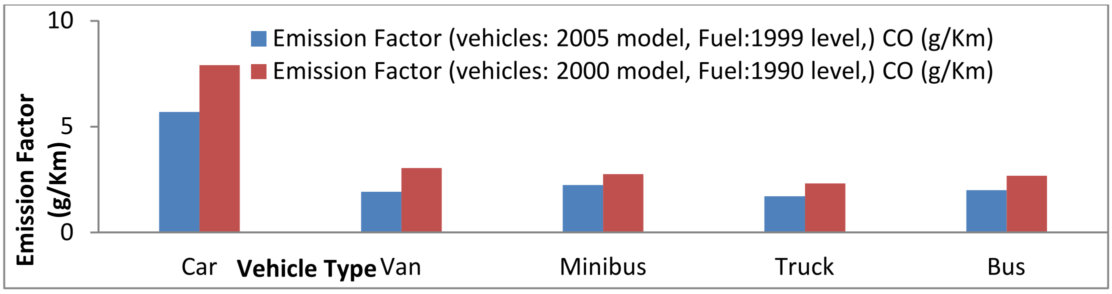
7.2. Impact of fuel and engine quality

The air quality is directly related to fuel consumption. Pakistan has opted Euro II standards for vehicles, namely Pak II, in 2009. The fuel quality in Pakistan is almost of 1990s levels of Europe. The benzene content (about 3.7-5%) in petrol used in Pakistan is very high (Yasin et al., 2008). Similarly, the concentration of sulfur is considerably high in diesel (0.5-1%) and furnace oil (1-3.5%) as compared to international standards (Martin et al., 2006). Consumption of fossil fuels has been increasing at the rate of about 6 % per annum. Half of the petroleum products are being used by the transport sector in Pakistan. Some South Asian countries have minimized the sulfur content in diesel to 0.035 % and furnace oil to 0.5 % (Martin et al., 2006). In India, numbers of green policies were introduced in Delhi, under the direction of Supreme Court of India. The content of sulfur in diesel (1%) and petrol (0.2%) were minimized to 0.05% from 1996 to 2001. The commercial vehicles were converted to CNG and 15 year old automobiles were banned in the city (Narain and Krupnick, 2007). Recent studies by Mofijur, Imdadul, Kumar and Ali, have shown reduction in certain pollutants due to introduction of certain biofuels in the ordinary fuels (Mofijuret et al., 2016; Imdadul et al., 2016; Kumar et al., 2016; Ali et al., 2016). A high level of fuel quality is required to achieve better level of Euro standards in the country like Euro III, Euro IV etc.

The decrease in sulfur contents in petrol, diesel and furnace oil, and decrease in benzene contents in petrol, can improve the emission factor of different vehicles. Vehicles can only achieve the better Euro standards like Euro III to Euro VI with provision of better quality of fuel and installment of catalytic converters in the vehicles. The hard measures can be taken four luxury vehicles at least to install catalytic converters and to pay tax on certain roads. More over catalytic converters can only be useable in vehicles with provision of very low content of sulfur (0.05% or less) (Martin et al., 2006). The emission factor of SO_2 and benzene depend upon their concentration in fuels. Therefore, emission factor of SO_2 and benzene can be improved through provision of better quality fuel with low benzene and sulfur contents. The emission factor of CO, NOx and PM can be improved through improved engine technology and installation of catalytic converters. A comparison of emission factor of vehicles with different models and fuel quality has been shown in Fig. 7.2. The comparative results revealed a considerable reduction in emission factor with improvement in model and fuel quality as shown in Fig. 7.2. It has been observed that category I buses (2005 model, 1999 level fuel) have 1.3 times less benzene, NOx and CO emissions as compared to category II buses (2000 model, 1990 level fuel). Category I trucks have 1.3 times less benzene and 1.4 times less NOx and CO emissions as compared to category II. Category I cars have 8.4, 1.5 and 1.4 times less benzene, NOx and CO emissions respectively, as compared to category II cars. Category I vans have comparable reduction in emissions like category I cars.

Category 1 minibuses have comparable reduction in emissions like trucks and buses. It is quite possible for a developing country like Pakistan to opt fuel quality level of 1999 and 2005 model's standard vehicles, as of Europe.





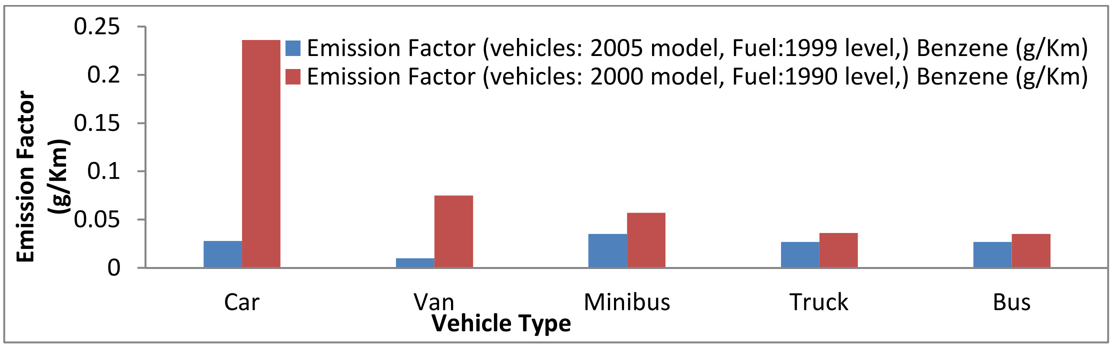


Fig. 7.2. Comparison of emission factor of vehicles with different models and fuel quality in Europe (at average speed of 40 Km)

7.3. Impact of road width

The road width has direct impact on traffic produced turbulence. Semi-Empirical Urban Street (SEUS) model is designed on the formula i.e. inverse relation between emission concentration and road width.

$$C \propto 1/W$$

$$C = E\,\mu s^{-1}\,W^{-1} + Cb \qquad (7.1)$$

In “eq. 7.1”, E is the emission rate over specified length, C is the model concentration of pollutant within the street, µs is the dispersion velocity, W is street width and Cb is background concentration (Venegas et al., 2014).

Therefore, road width has direct impact on pollution level on roads. Roads with greater number of lanes, green belts, greater speed of vehicles (up to 60 Km/hr), low adjacent building heights, have low concentration of pollutants. The pollution level is low at Gulberg main boulevard road as compared to Mall road, Multan road and Ferozepur road due to greater width, high speed of vehicles and signal free track. Questionnaire survey depicts that people demand wide roads to combat congestion, improve speed and better dispersion of air pollutants.

7.4. Impact of signal free tracks

The reduction in most of the pollutants has been observed with increase in speed to an optimum level. But the NOx emissions increase with increase in speed for diesel vehicles. In Lahore, most of the personal cars and all the motorcycles use petrol as fuel. Only the loader trucks and some buses use diesel as fuel. Therefore, increase in speed to an optimum level of 40-60 Km/hr definitely results in minimization of urban emissions. More over with provision of signal free tracks, congestions, number of cold starts and fuel usage are decreased. Questionnaire survey depicts that road users are happy with introduction of signal free tracks as it reduces congestion, improves speed and reduces vehicular air pollution. The monitoring results also shows that air quality is better on wide and signal free roads like Gulberg road and Jail road; while pollution levels are high on signals and congested roads like Ferozepur road. The trend of vehicular exhaust pollutants for Euro II gasoline cars (cc: < 1.41), generated by OSPM is shown in Fig. 7.3.

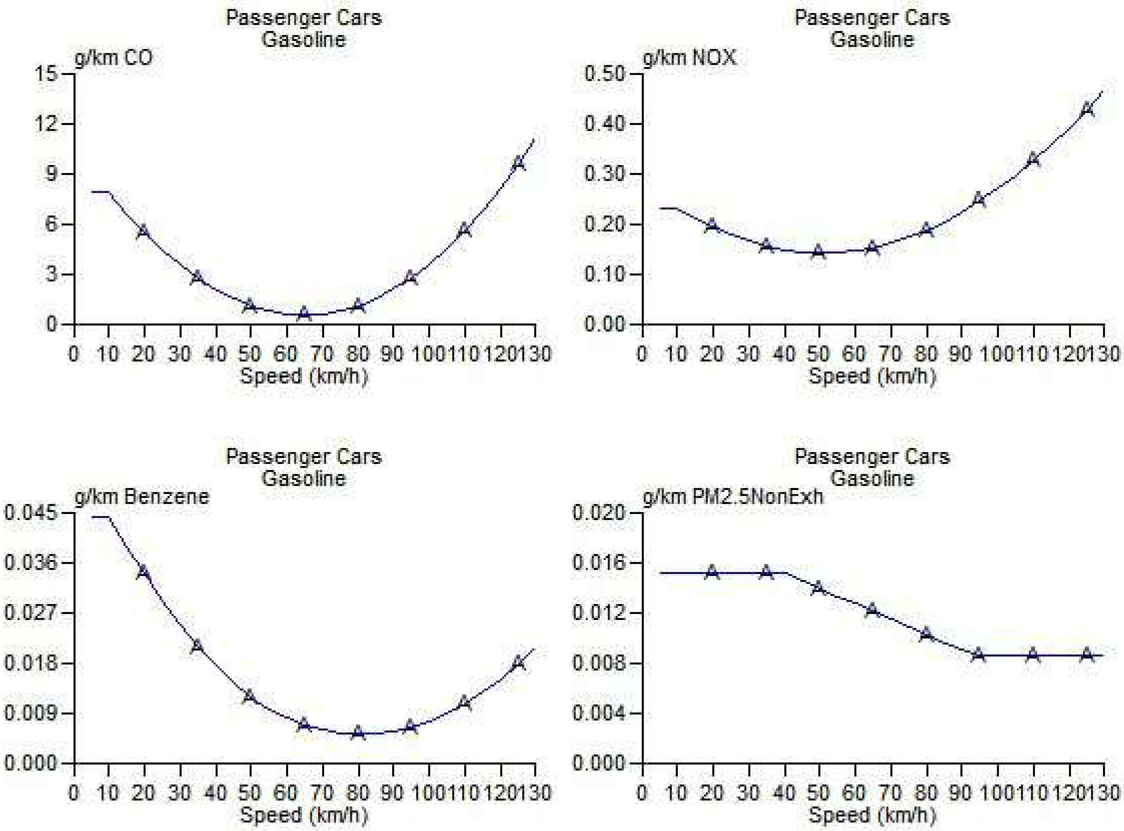


Fig. 7.3. Vehicular exhaust emissions Vs speed

7.5. Impact of land use developments and electronic technologies

Land use developments, like provision of public transport to every citizen at 10 minutes' walk, mix developments (markets and homes at same place), vegi-gardens and kitchen gardens, provision of facilities (markets, hospitals, educational institutes, industry) at grass root level, facilities for pedestrian, cyclist and disables etc, can definitely reduce the travelling and use of personal cars. The provision of basic facilities at grass root level is necessary to stop migration from small cities and rural areas, to big cities. The introduction of industrial estates in small and new cities, are necessary to prevent unstoppable scattering of big cities. There is also need to promote vertical development and small homes for better land use. The strict EIA conditions must be implemented for new housing schemes. There is need to declare land as agricultural, industrial, protected, residential land or any other prescribed region. Similarly, use of internet facilities like e-billing, online money transfer, online meetings, video conferences, mobile billing, hologram and ATM cards, and use of modern technologies like active transport management (ATM), intelligent transport system (ITS), is necessary to control the traffic issues. All these measures can reduce the burden on big cities with reduction in urban emissions. The questionnaire survey depicts that use of electronic technologies like e-billing, online money transfer and video conference has been increasing among public. But public as well as concerned departments have very little knowledge about sustainable land use developments. But each questioned person is convinced that sustainable land use developments will be very helpful in minimization of private cars and improvement of air quality. The reduction in emissions with reduction in number of cars has already been shown in Table.7.2.

7.6. Summary

The indicators of transport sustainability deal with social, economic and environmental issues. Developing countries lack policies regarding urban development, land use planning and introduction of modern tools in many sectors. Traffic signals do not remain alive in electric power shortage hours due to their non-conversion on solar energy on most of the crossings. Traffic jams are observed on many crossings in case of electric power shortage. Fuel quality is not up to standards throughout the country. Euro II standards have been introduced in the country but fuel quality is not of Euro II standards (0.05 % sulfur in diesel). More over the condition of vehicles, especially of trucks and buses, keeps on getting poorer with passage of time, after purchase of these vehicles. It has been calculated that a 2005 model car with 1999 level fuel quality has 8.4, 1.5 and 1.4 times less benzene, NOx and CO emissions respectively, as compared to 2000 model car with 1990 level of fuel as that of Europe. PM_{10} and SO_2 emission factors have very little effect of gain in speed. A considerable decrease in CO (33.2%) and benzene (25.7%) emissions have been observed with gain in 10 Km/hr speed (from 40 to 50 Km/hr) and decrease in 10% number of cars. Substandard quality of fuel and vehicles make emission factors much greater than international standards. Most of the citizens are poor and illiterate in the city. People do not use modern electronic ways like e-billing, video conference etc, for their routine tasks. Similarly, most of the homes have no place for kitchen gardens and new housing societies are not bound to make vegi-gardens.

The questionnaire survey depicts that road users are happy with steps like widening of roads and introduction of overhead bridges & underpasses, as it is helpful to reduce congestions, improve speed, save time and to reduce vehicular air pollution. Use of electronic technology has been increasing very swiftly among public. People are also convinced that sustainable land use developments will reduce number of private trips and will promote public transport. Public is also convinced to improve fuel quality and engine efficiency. But most of the people have very little or no knowledge about the sulfur and benzene levels in the fuel.

The monitoring results depicts that air pollution levels are relatively low on wide and signal free roads like Gulberg and Jail road. While air pollution is high on signals and congested roads like Ferozepur road.

CONCLUSIONS AND FUTURE RECOMMENDATIONS

CHAPTER 8

8. Conclusions and future recommendations

8.1. Conclusions

Different aspects of transport related air pollution have been analyzed in the study:

1. The ratio analysis of the background data of the Lahore city revealed that mobile sources are the dominant source of air pollution in the city. As the ratio results of background air quality monitoring station matches more to road air quality data, revealing that mobile sources are major source of air pollution in the city.
2. The annual average concentrations of $PM_{2.5}$ and NO exceed the Pak-NEQS. The hourly average levels of ozone exceed the Pak-NEQS during the summer season. CO and SO_2 levels remain in compliance with the Pak-NEQS for the entire calendar year. SO_2 emissions mostly remain within NEQS in Lahore, as most of the automobiles use petrol as fuel. The level of SO_2 emissions remains relatively high in industrial areas due to use of diesel as fuel. CO emissions remain relatively high in urban areas as compared to industrial areas, due to use of petrol and CNG as fuel by most of the mobile sources. NOx are abundantly produced by both 4-stroke petrol engines and diesel engines, therefore, the concentration of NOx mostly remains high in Lahore city.
3. Air quality of different sites has been compared in and around the Lahore. The rural area showed most improved air quality. The urban background showed less pollution than road side, traffic hotspots and industrial area. But CO emissions were low in industrial area as compared to road side and urban background, due to less use of petrol or CNG in the industrial area. SO_2 emissions were high in industrial area as compared to any other site, due to use of diesel and coal in the

industry. As the NOx are produced by both 4-stroke petrol engines and diesel engines, therefore NOx emissions were comparable at road side and industrial area. $PM_{2.5}$ levels remained very high at all spots. Especially during November $PM_{2.5}$ level remains as high as to act as visible smog and to lower the visibility to considerable extent, due to multiple reasons.

4. The ratio analysis showed that mobile sources are the major sources for CO and NOx, while point sources are the major source for SO_2 emissions in the urban area of Lahore. The diurnal trend of pollutants is similar to monthly pattern i.e. AQI remains low at day-time (in a day) and in summers (in a calendar year). But ozone level remains high during summer season due to high solar radiations. The concentration of primary pollutants like NO, NO_2, NOx, CO, SO_2, CH_4, NMHC and $PM_{2.5}$ remains low at day-time due to their use either as precursor of O_3, or due to dispersion effect and many other factors. The ozone level remains high at day-time (like in summers) due to high solar radiations and presence of high concentration of its precursors. The primary pollutants like NO, SO_2, CO, CH_4 etc have inverse correlation with O_3. A direct correlation has been observed between O_3 and solar radiations.
5. Almost all the NO has been converted to NO_2 by reacting with O_3 at day time, in the presence of high solar radiations; thereby confirming a true negative correlation between NO and O_3; and showing that O_3 has been consumed by NO to produce NO_2; and all the available O_3 has might been produced due to VOCs are other precursors, when NO is nil.
6. High air quality index (AQI) has been observed form November to February (low rain fall season) due to multiple reasons like very low rain fall, low wind speed, inversion due to low temperature (winter season), low mixing height, less

dispersion, burning of crop residues etc. Especially, highest AQI has been observed in November, which may result in increased smog and health concerns in the region in the coming years.

7. Motorcycles and cars are 65% and 26% of the registered vehicles in Lahore, respectively. The social survey concludes that people avoid using public transport due to issues like time, cost, convenience, and distance from bus stop. The social survey pointed out that distance from bus stop, time taken and length of journey ($\geq$ 4 out of 5 grades) were considered as important factors in preventing people from using public transport. Time, convenience, safety, reliability, relaxation and health ($\geq$ 4 out of 5 grades) were considered important in the choice of public transport, during survey. Cheaper fares, availability of school/work bus, more reliable service, more bus routes and extended bus service ($\geq$ 4 out of 5 grades) were considered as important factors to promote public transport. None of the advertisement technique was ranked above 4 to promote public transport, showing that only advertisement techniques can not convince people to use public transport.
8. In this study, the main indicators of transport sustainability like “shifting of modes from private to public vehicles”, “land use planning” and “sustainable operations” have been studied under different sub indicators. A total of 35 indicators have been selected to calculate the transport sustainability index on different roads of Lahore. Transport sustainability index of Ferozepur road, Gulberg main boulevard road, Jail road, Mall road and Multan road remained 47.14, 38.57, 40, 34.29 and 34.29 respectively.
9. During the survey, it has been observed that despite of number of steps taken by the Government, to improve the traffic flow through introduction of underpasses,

overhead bridges and lengthy U-turns; still the pedestrians, cyclists and poor rickshaw users are ignored in this development. New housing societies have no or very less provision of public transport within the societies. People and policy makers were not found well aware of the new sustainable ideas of kitchen gardens, vegi-gardens, e-billing, green roofs, environmental designs, road taxes, use of parking plazas, active transport management (ATM), travel demand management (TDM) etc. The sustainability index of the studied roads is very low (< 50) due lack of policy measures in terms of land use planning and TDM measures to promote public transport, cycle, walk and renewable energy resources etc.

10. Urban air pollution has negative correlation with transport sustainability measures. Road width, better fuel quality, advance engine type, signal free roads, mix developments, use of electronic technologies are found to have positive impact on improvement of air quality. It has been observed that buses with 2005 model and 1999 level fuel, emit 1.3 times less NOx, benzene and CO emissions in comparison to 2000 model buses with 1990 level fuel (as of Europe). Similarly, 2005 model with 1999 level fuel emit 8.4, 1.5 and 1.4 times less benzene, NOx and CO emissions respectively, as compared to 2000 model cars with 1990 level fuel (as of Europe). The questionnaire survey depicts that road users are happy with wide and signal free roads as it improves speed of vehicles, combats congestions and improves air quality on roads. The monitoring results also depicts that air quality is better on wide and signal free roads (like Jail and Gulberg roads) than congested roads (like Ferozepur, Mall and Multan roads).

11. Reduction in number of cars can also improve the speed of vehicles, which can result in reduction of emissions, especially CO and benzene emissions. It has been

calculated that only 20% decrease in number of cars and 10 Km/hr gain in speed (from 40 to 50 Km/hr) can reduce CO and benzene emissions of cars to 40.7% and 34% respectively. A very little change has been observed for emission factors of NOx, SO_2 and PM_{10} with gain in speed from 40 Km/hr to 50 Km/hr.

12. Most of the community was found hesitant to use public transport. Schools, Government offices, private offices and commercial markets have different open and closing timings, which is blessing to control traffic load. Peak hours have been observed from 8-10 am, 1-3 pm and 6-8 pm on almost all the observed roads. Motorcycles have low buying and operational cost, which make them main feature (53 %) of traffic in Lahore. Cars and autorickshaws with their 31 % and 10 % contribution respectively were also a big load on traffic in Lahore. Despite of no significant peak hours and use of motorcycle by majority of the citizens, still congestions are frequently observed on many roads.
13. One of the main tasks in modeling of air pollution was determination of emission factor of different vehicle classes. The emission factors of seven different classes of vehicles have been calculated according to their fuel quality, engine type and average speed. Air pollution has been modeled on five main roads of Lahore with OSPM, with provision of background urban emissions & meteorological data, diurnal vehicle count data, average speed of vehicles and street configuration data. A significant correlation (r-value > 0.5) has been observed between modeled and monitored results. As the background pollution level is considered always less than the road pollution level by the OSPM software, the modeled results for relatively clean areas like Gulberg road have shown less correlation. The better modeling results have been observed for Mall road, Multan road and Ferozepur road, which are relatively more polluted zones. For the Mall road for example, the

r-value for SO_2, NOx and CO (0.92, 0.92 and 0.88 respectively) is much significant.

8.2. Recommendations for future work

1. A lot has yet to be done regarding air quality monitoring in Pakistan. Background air quality monitoring stations have only been installed in provincial and federal capitals. Background air quality of other cities, rural areas, mountains, deserts etc is not known. A comprehensive study is required to monitor the background air quality data of different cities, rural areas, mountains, deserts and other ecological regions of Pakistan. A research project can also be launched to set NEQS for different regions like plain areas, plateaus, mountains, seaside, desert and reserved areas.
2. Trans-boundary air pollution is a very hot issue among and between different countries. A lot of debate has been observed between India and Pakistan, complaining each other regarding trans-boundary air pollution level. A consistent and comprehensive study is required to monitor the pollution level at international boundaries, especially on India-Pakistan border. The correlation of air pollution levels with wind direction is key to assess the trans-boundary air pollution intervention.
3. Urban driving cycle has yet not been defined for any class of vehicle, in Pakistan. Many other nations including India have defined the urban driving cycle for different classes of vehicles. Urban driving cycle is a key factor to determine the emission factor of different classes of vehicles. A comprehensive study may be launched to define urban driving cycle in different regions/cities of Pakistan. The emission factor can then be defined on the basis of urban driving cycle, fuel quality, and engine type.
4. Transport sustainability indicators may differ for each city according to local requirements and capacity. A comprehensive study may be launched to set transport sustainability indicators at national level for small cities, big cities and rural areas. Research projects may be launched in collaboration with various departments and educational institutes to formulate transport sustainability indicators and policy.

5. Modeling is useful technique to predict certain parameters in a certain field. A lot of research projects can be launched in collaboration with mathematics department, to introduce certain models in many fields. Regarding air pollution, new local models should be introduced in the field of indoor, ambient, point, mobile and trans-boundary air pollution.
6. Worldwide different models are available to model indoor, urban, road and regional air pollution levels. Comprehensive studies can be launched to model urban, indoor, road and regional air pollution levels through different available models.

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ANNEXURE

Annexure-I

Transport Sustainability - Questionnaire

This questionnaire is a part of PhD research to calculate transport sustainability of different area of Lahore, Pakistan, by GC University Environmental Science Department (SDSC)

The research aims to:

a) Search the motives, reasons and barriers to using public transport and private transporting in different areas of Lahore Pakistan

b) Determine the possible incentives and steps to encourage people to use walk, bicycle or public transport

1. Personal Information:
   Name: ____________________________ Gender: _______________ Profession: _____________

   Age: _____________ Email Address__________________________ Education: _______________

   Address:

   ____

	0	1	2	3
Do you own	Nothing	Car	Motorcycle	Cycle
	☐	☐	☐	☐

2. Which method of transport do you use most frequently for the following journeys:

	1 Walk	2 Metro	3 Bus/ Wagon	4 Taxi/ Rick	5 Cycle	6 Car	7 Motorcycle
Job/ Education	☐	☐	☐	☐	☐	☐	☐
Leisure/ Fun	☐	☐	☐	☐	☐	☐	☐
Shopping	☐	☐	☐	☐	☐	☐	☐
Work	☐	☐	☐	☐	☐	☐	☐
Other……………………	☐	☐	☐	☐	☐	☐	☐

3. Rate how important are the following factors in preventing you from using public transport: (1=very important 5=not important)

	1	2	3	4	5
Lack of available information	☐	☐	☐	☐	☐
Distance from bus stop/train	☐	☐	☐	☐	☐
Cost	☐	☐	☐	☐	☐
Length of journey	☐	☐	☐	☐	☐
Total time taken	☐	☐	☐	☐	☐
Weather	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Frequency of service	☐	☐	☐	☐	☐
Other……………………………	☐	☐	☐	☐	☐

4. Rate how important are the following factors in selection of your choice of transport: (1=very important 5=not important)

	1	2	3	4	5
Relaxation	☐	☐	☐	☐	☐
Health	☐	☐	☐	☐	☐
Environmental benefits	☐	☐	☐	☐	☐
Cost	☐	☐	☐	☐	☐
Weather	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Time taken	☐	☐	☐	☐	☐
Convenience	☐	☐	☐	☐	☐
Route	☐	☐	☐	☐	☐
Other……………………………	☐	☐	☐	☐	☐

5. Rate how effective you think the following initiatives would be to encourage sustainable transport use: (1=very effective 5=not very effective)

	1	2	3	4	5
School/Work Bus	☐	☐	☐	☐	☐
More bus routes	☐	☐	☐	☐	☐
Cheaper Fares	☐	☐	☐	☐	☐
Less parking space	☐	☐	☐	☐	☐
Extended Bus service	☐	☐	☐	☐	☐
Higher parking fees	☐	☐	☐	☐	☐
More and Free cycle parking	☐	☐	☐	☐	☐
Parking at Metro Bus Stops	☐	☐	☐	☐	☐
Car-sharing scheme	☐	☐	☐	☐	☐
On-board Entertainment	☐	☐	☐	☐	☐
Cycle lanes	☐	☐	☐	☐	☐
Cycle/Pedestrian U turn bridges	☐	☐	☐	☐	☐
More reliable service	☐	☐	☐	☐	☐
Other……………………………..…	☐	☐	☐	☐	☐

6. Rate how effective are the following methods to promote the sustainable transport, (1=very effective 5=not very effective)

	1	2	3	4	5
Posters	☐	☐	☐	☐	☐
Leaflets	☐	☐	☐	☐	☐
Television advert	☐	☐	☐	☐	☐
E-mailed adverts	☐	☐	☐	☐	☐
Hoardings/ Billboards	☐	☐	☐	☐	☐
Radio adverts (Ram Air)	☐	☐	☐	☐	☐
Advert inBuses	☐	☐	☐	☐	☐
Text Messages	☐	☐	☐	☐	☐
Web page/Social Media	☐	☐	☐	☐	☐
Other……………….……………	☐	☐	☐	☐	☐

7. Do you have any other comments you would like to make?

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……

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Publications

Publications

Haider, R., Yasar, A., & Tabinda, A. B. (2017). Urban Emission Patterns at a Semi-Arid Site in Lahore, Pakistan. *Polish Journal of Environmental Studies*, *26*(1), 59-68.

Haider, R., Yasar, A., & Tabinda, A. B. (2017). Impact of Transport Sustainability on Air Quality; A Case Study of Lahore Pakistan. *Current Science*, Accepted on 14/11/2017.

Pol. J. Environ. Stud. Vol. 26, No. 1 (2017), 59-68
DOI: *10.15244/pjoes/64284*

Original Research

Urban Emission Patterns at a Semi-Arid Site in Lahore, Pakistan

Rizwan Haider, Abdullah Yasar*, Amtul Bari Tabinda

Sustainable Development Study Center, GC University, Lahore Pakistan

Received: 25 April 2016
Accepted: 18 July 2016

Abstract

The current research is an attempt to find out diurnal and monthly mean patterns of air pollutants, their interrelationships, and their dominant sources through hourly and monthly data analysis. Lahore is a semi-arid region with low rainfall, hot and humid summers, and cold dry winters. Annually, the highest air quality index (AQI) (132 to 185) is observed from November to February due to inversion at low wind speeds (<1.5 m/s monthly average), low temperature (15ºC to 21ºC monthly average), and low solar radiation (104 to 140 W m-2 monthly averages). AQI remained low (74 to 85) from June to August due to relatively heavy rain, relatively high wind speed (1.59 to 1.85 monthly averages), dispersion due to high temperatures, high solar radiation, and summer vacations to schools. With an analogous diurnal trend, the AQI remains stumpy in daytime. The high CO/NOx ratio indicates that mobile sources are dominant contributors to NOx; and the low SO_2/NOx ratio indicates that point sources are dominant contributors to SO_2. CO has a significant positive correlation with NO, NO_2, NOx, CH_4, SO_2, and RH, and a negative correlation with O_3 and temperature. This explains why four-stroke petrol engines are common sources for CO, NO, NO_2, and NOx. $PM_{2.5}$ has a significant positive correlation with SO_2, which explains why diesel engines are a common source for $PM_{2.5}$ and SO_2. O_3 has a significant negative correlation with NO, NO_2, NOx, CH_4, CO, and RH; and has a significant positive correlation with temperature and solar radiation.

Keywords: semi-arid, mobile sources, air pollution, meteorology, air quality index, Pakistan

Introduction

The population of Lahore is 9 million, making it Pakistan's second largest city [1]. There are 2.7 million vehicles along with 1,986 different industrial units in Lahore [1]. The ambient air pollution in the city predominantly originates from vehicular and industrial emissions [2] .

The semi-arid climate of Lahore naturally favors the accumulation of pollutants. Solid aerosols are present in the samples of PM [3].

New housing schemes have not been found to fulfill the needs of sustainable development and transport sustainability. The city district government has failed to achieve its target of ambient air quality improvements under the 2001 devolution plan due to the absence of transport policy, alteration in land use policy, and deprived management and monitoring of air quality [4]. Furthermore, the city has been expanding due to migration from small cities of Punjab. Migration has been observed

*e-mail: yasar.abdullah@gmail.com

from Karachi and Peshawar as well, due to security reasons.

Diesel-fueled generators have been used extensively in industrial sectors (point sources) as well as in other sectors due to widespread power shortages in the country, which adds a lot to urban ambient air pollution [5]. The use of diesel fuel by mobile sources contributes a lot to particulate matter air pollution [6]. The sulfur contents are very high in diesel (0.5-1%) and furnace oil (1-3.5%) being used in Pakistan, whose fallout comes with higher sulfur dioxide pollution [7].

The environmental damage is associated with health issues. Currently, mobile sources have been found to promote high levels of tropospheric ozone and health concerns in urban areas [8]. The Organosulfatese have been identified and quantified in fine particulate matter ($PM_{2.5}$) collected in Lahore, Pakistan, in 2007-08 [9]. Enhanced diastolic blood pressure has been found to be associated with long-term exposure to NO_2 and $PM_{2.5}$ in those children who used to live at the same place since birth [10]. The $PM_{2.5}$ levels have been exceeding the NEQS in four provincial as well as federal capitals of Pakistan [11]. In the fall season during October and November; burning of crop residues in eastern Pakistan and northwestern India increase the concentrations of $PM_{2.5}$ in the atmosphere [12, 13]. Secondary inorganic PM in the form of sulfates and nitrates is formed by the oxidation of SO_2 and NOx. However, the organic carbon fraction is formed due to oxidation of VOCs [14, 16]. This process is enhanced by ammonia [17]. The black carbon aerosols are present in 90% of $PM_{2.5}$ in winter and contribute about 5-15% to overall $PM_{2.5}$ in the ambient air [18, 19]. Black carbon has been found to be at much higher levels during foggy season. Black carbon has also been found to be trapped in aerosols during the foggy season, resulting in a lessening of solar radiation [20].

Other big cities in Punjab also have high pollution levels. Concentrations of CO, NO_2, and SO_2 have been found above NEQS levels in Faisalabad [21]. The traffic pollution has been found to be the most contributing factor to outdoor air pollution in most urban areas [22].

Brick kilns on the outskirts of Lahore are also a great point source of air pollution. A study of brick kilns in the Wahga and Batapur areas of Lahore revealed that the conventional Bull's Trench Brick Kiln are being used in Lahore, which comprises no control measures to manage the air pollution. Modern brick manufacturing technologies such as vertical shaft brick kiln must be introduced to control the air pollution [23].

It is impossible to monitor the spatial and temporal variations in the atmosphere on the basis of a single monitoring site [24]. In a recent study on some metals in the vehicular exhaust emissions of rickshaws, it has been discovered that a significant boost has been found in Al, P, and Zn in the PM samples of four-stroke Rickshaws [25]. In another study in Beijing, perfluorinated compounds (PFCs) are found in ambient $PM_{2.5}$, PM_{10}, and TSP [26]. The environmental damage costs the country an annual loss of about Rs. 365 billion, of which the urban air pollution loss was approximately Rs. 65 billion in 2006 [27].

Materials and Methods

Hourly air quality monitoring data for 2007-11 and 2014-15 were collected from the Provincial Environmental Protection Agency. The air quality monitoring stations remained almost out of work during 2012 and 2013 due to lack of budget to run them. Fix and mobile air quality monitoring stations had been used to monitor the six major pollutants along with meteorological parameters. The air quality monitoring stations contain an anemometer (KoshinDenkiKogyo Co., Ltd. Model KVS 501) combined wind vane, a solar radiation meter (Koshin Denki Kogyo Co., Ltd. Model SR-010), a thermohygrometer (Koshin Denki Kogyo Co., Ltd. ModelHT-010), and a data logging system (Horiba, Ltd. Model Special).

The six major air pollutants like ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), oxides of nitrogen (NOx, i.e., NO and NO_2), fine particulate matter ($PM_{2.5}$), and hydrocarbons (total hydrocarbons, non-methane hydrocarbons, and methane) were determined through analyzers described in Table 1.

The air quality index (AQI) was calculated according to "Eq.1" [28].

Table 1. Detail of instruments of air quality monitoring station.

Pollutant	Analyzer	Range	Method	Detection Limit
CO	Horiba Ltd; Model APMA-370	0~50 ppm	non-dispersive infrared ray method (ISO4224)	0.1ppm
NO/NO_2 /NOx	Horiba Ltd; Model APNA-370	0~1 ppm	Chemiluminescence (ISO7996) method	0.5 ppb
Sulfur dioxide	Horiba Ltd; Model APSA-370	0~0.5 ppm	U.V. fluorescence method (ISO10498)	1ppb
Ozone	Horiba Ltd; Model APOA-370	0~1ppm	UV photometry method	0.5 ppb
Hydrocarbon	Horiba Ltd; Model APHA-370	0~50 ppmC	Converter oven method	0.1 ppmC
$PM_{2.5}$	Horiba Ltd; Model APDA-370	0~5 mg m^{-3}	β-ray absorption method (ISO6349)	

$$AQI = [(NO_2/80) + (SO_2/120) + (O_3/130) + (CO/5) + (PM_{2.5}/35)]/5 \ X \ 100 \quad (1)$$

Lahore and its Meteorology

Lahore is located at 31°32′N 74°22′E at 217 m above sea level. The municipal area of Lahore is 332 km^2. Due to rapid urbanization, the area has been extended to 1,000 km^2. Two fixed air quality monitoring stations have been installed in Lahore to monitor air quality. One of the stations is installed on the second floor of the city hall building situated in the northern main commercial area of Lahore with a number of busy roads, markets, and dense population. The second station was installed in Quaid-i-Azam Township area, a southern residential area near Kotlakhpat industrial estate.

The city hall air quality monitoring station was selected for data analysis. The fixed air quality monitoring station installed at city hall on Lower Mall road in Lahore represents the ambient air quality of the main city of Lahore. The monitoring station was located about 8 m from the ground. Most of the main roads of Lahore are within a 1-3 km sphere of the station. The location of the two fixed Air Quality Monitoring Stations can be seen in Fig. 1.

The climate of Lahore can be distributed into five seasons: foggy winter (15 Nov-15 Feb) with low rainfall, low wind speed, and high inversion; spring (16 Feb-5 April) with low rainfall and moderate temperature (T); summer (15 April-June) with high temperature, high rainfall, low relative humidity (RH), and high dispersion effects; rainy monsoon (July-16 September) with high temperature, high relative humidity, and low pollution due to dispersion and washing effect; and dry autumn (16 September-14 November) with low wind speed and low RH [29].

June is the hottest month, with an average temperature of 33.9ºC. The average temperature of January is 12.8ºC, which makes it the coolest month of the year. The average annual temperature of Lahore is 24.3ºC, which is fairly hot as annual average. Average monthly temperature range is 21.1ºC. The average daily temperature variation is 15.5ºC [29].

Minimum average sunshine has been observed in January with 6.9 hours day^{-1}. Overall annual average sunshine is 8.4 hours day^{-1} [29].

Wind speed remains low almost throughout the year except some windy days in summer. Around 60% of the year remains calm and 33% of days see an average speed of 1-3 knots. Only 6% of the year experiences speeds of 4-6 knots. Wind direction remains mostly northwest during monsoon and summer and southeast during winter [29].

Relative Humidity (RH) remains low throughout the year except during monsoon season. The monthly average of relative humidity exceeds 60% during July, August, and September. Average relative humidity remains around 77% in the morning and 40% in the evening. The average monthly relative humidity ranges around 20% in May to 58% in August. Overall, the annual average relative humidity remains around 37.9%.

The climate of Lahore has observed extreme weather events in the near past. The highest ever recorded temperatures of the city were 48.3ºC on 30 May 1944 and 48ºC on 10 June 2007. The highest recorded rainfall was 221 mm, observed on 13 August 2008, and 4.5 mm hail was observed in Lahore on 26 February 2011 [29].

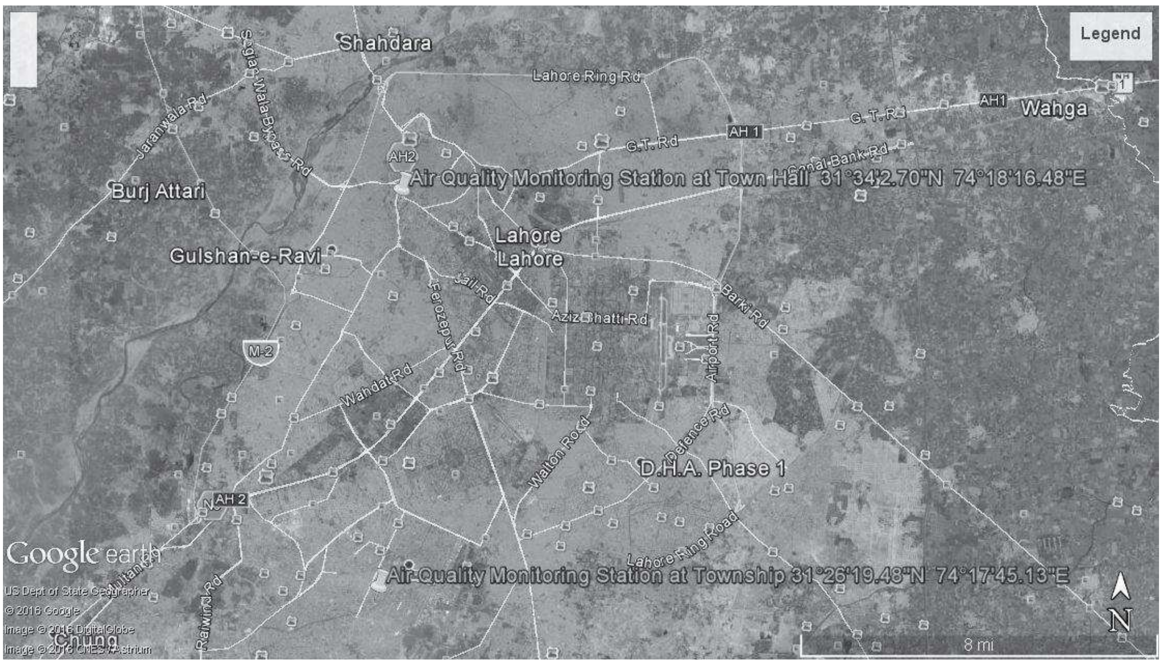

Fig. 1. Locations of automatic fixed air quality monitoring stations in Lahore (based on Google map).

Table 2. Air quality index.

AQI	0-50	50-100	101-150	151-200	201-300	>300
Air Quality	Clean	Moderate	Unhealthy for sensitive	Unhealthy	Very Unhealthy	Hazardous

Results and Discussion

Ambient air quality data of Lahore for 2007-11 and 2014-15 has been analyzed to discern patterns and determine the sources of the six representative air pollutants. The hourly data for each pollutant collected was analyzed for average concentration, monthly mean pattern, and seasonal and diurnal variations.

Air Quality Index

The interpretation of AQI can be elaborated as clean, moderate, unhealthy, and very unhealthy. The Pakistani NEQS for O_3 for 24 hours has yet not been made available. The NEQS for O_3 for one hour have been revised from 180 to 130 and for $PM_{2.5}$ for 24 hours have been revised from 40 to 35 since January 2013 [30]. So before January 2013, the index value would be calculated accordingly. A projected AQI is given in Table 2 [28].

AQI remains low (~74 to ~85) from June to August due to heavy rain, relatively high wind speed (~1.59 to ~1.85 monthly average), and dispersion due to high temperatures and high solar radiation. In summer, an improved air quality index also has been observed in northern China. [31].

The highest AQI (~132 to ~185) was observed from November to February due to inversion at low wind speed (< 1.5 m/s monthly average), low temperature (~ 15-21ºC monthly average), and low solar radiation (~104-140 W m^{-2} monthly averages) due to heavy fog during December and January**.** Another reason for the high AQI during fall can be due to burning crop residue in southwestern India and eastern Pakistan. The wind direction during winter remains mostly southeast, which can also be a reason for contributing to pollution in Lahore from a number of polluted steel industries in the northern part of Lahore and industrial clusters in Sheikhupura and Gujranwala. The steel industries are mostly located in Badami Bagh, Misry Shah, Daroghay Wala, and around the Band Road area in northern Lahore. Fig. 1 shows a map of Lahore.

Data Analysis

For data analysis, the data of daytime (07:00-15:00) has been taken for analysis of ozone and its precursors. The data of a sunny and clear day has been taken. The mean concentration of the ozone, other pollutants, and meteorological parameters are given in Table 3.

The day is dry and hot with low mean RH (30.66), high solar radiation (about 680 W m^{-2}), and high mean temperature (around 38ºC). Wind speed remained low (mean value = 1.72 m/sec) as a routine matter in semi-arid regions. NO remained almost nil (mean value = 1.93 µg m^{-3}) during sunny hot days due to its conversion to NO_2 (mean value = 26.8 µg m-3) in the presence of high concentrations of O_3 (mean value = 122.50 µg m^{-3}). Concentrations of CH_4 remained below (mean value = 2,210.61 ppb) its natural level (around 3,000 ppb) due to its consumption as a precursor of ozone. The mean value of $PM_{2.5}$ (155.07mg m^{-3}) remained high due to a high amount of un-burnt carbon from vehicular exhaust emissions in the atmosphere.

Correlation Analysis

Table 4 shows the correlation of different air quality parameters. The following results are made according to statistical analysis of data in Table 4.

O_3 has a significant negative correlation with NO, NO_2, NOx, CH_4, CO, and RH (r-value> -0.5); and has significant positive correlation with T and solar radiation (r-value> 0.5). The level of tropospheric ozone is highly dependent on solar radiation and atmospheric temperature [32], while NO has significant positive correlation with NO_2, NOx, CH_4, CO, and RH (r-value> 0.5 for each); and has negative correlation with O_3, T, and solar radiation (r-value> -0.5 for each). NO concentration is almost negligible from 07:00-15:00 in the summers due to its conversion into NO_2 by reacting with abundant O_3 produced by different sources such as CO, NO_2, VOCs, and NMHCs in the presence of sunlight.

Table 3. Mean values of different pollutants and meteorological parameters (07:00-17:00).

Variable	NO	NO_2	NOx	CH_4	NMHC	CO	SO_2	O_3	$PM_{2.5}$	Wind Speed	T	RH	Solar radiation
Unit	µg m^{-3}	µg m^{-3}	Ppb	ppb	ppb	mg m^{-3}	µg m^{-3}	µg m^{-3}	µg m^{-3}	m/s	ºC	%	W m^{-2}
Mean Value	1.93	28.52	16.14	2210.61	735.85	0.68	42.64	122.50	155.07	1.72	37.68	30.66	539.35

Table 4. Correlation analysis of ambient air variables of semi-arid region, Lahore.

		NO	NO_2	NOx	CH_4	NHMC	CO	SO_2	O_3	$PM_{2.5}$	WS	T	RH	Solar radiation
NO	Pearson Correlation	1	.946**	.741**	.953**	.416	.917**	.556	-.825**	.163	.058	-.725*	.616*	-.614*
NO_2	Pearson Correlation	.946**	1	.871**	.978**	.254	.912**	.571	-.675*	.200	-.084	-.634*	.496	-.660*
NOx	Pearson Correlation	.741**	.871**	1	.797**	.039	.734*	.363	-.520	.072	-.138	-.401	.249	-.635*
CH_4	Pearson Correlation	.953**	.978**	.797**	1	.214	.892**	.576	-.714*	.094	-.003	-.710*	.571	-.717*
NHMC	Pearson Correlation	.416	.254	.039	.214	1	.336	.185	-.238	.497	-.157	-.135	.184	.245
CO	Pearson Correlation	.917**	.912**	.734*	.892**	.336	1	.809**	-.758**	.443	.224	-.805**	.737**	-.466
SO_2	Pearson Correlation	.556	.571	.363	.576	.185	.809**	1	-.516	.654*	.519	-.820**	.841**	-.160
O_3	Pearson Correlation	-.825**	-.675*	-.520	-.714*	-.238	-.758**	-.516	1	-.004	-.491	.824**	-.763**	.525
$PM_{2.5}$	Pearson Correlation	.163	.200	.072	.094	.497	.443	.654*	-.004	1	.045	-.189	.282	.487
WS	Pearson Correlation	.058	-.084	-.138	-.003	-.157	.224	.519	-.491	.045	1	-.678*	.769**	-.088
T	Pearson Correlation	-.725*	-.634*	-.401	-.710*	-.135	-.805**	-.820**	.824**	-.189	-.678*	1	-.978**	.523
RH	Pearson Correlation	.616*	.496	.249	.571	.184	.737**	.841**	-.763**	.282	.769**	-.978**	1	-.364
Radiation	Pearson Correlation	-.614*	-.660*	-.635*	-.717*	.245	-.466	-.160	.525	.487	-.088	.523	-.364	1

**Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed)

NO_2 has significant positive correlation with NO, NOx, CH_4, CO, and SO_2 (r-value> 0.5 for each), and has significant negative correlation with O_3, T, and solar radiation (r-value> -0.5). In daytime almost all the NO has been converted to NO_2 by reacting with O_3 in the presence of sunlight. The dominant sources of nitrogen oxides as far as vehicles are concerned are diesel and four-stroke engines [33].

NOx has a significant positive correlation with NO, NO_2, CH_4, CO, and SO_2 (r-value> 0.5 for each), and has a significant negative correlation with O_3 and solar radiation (r-value> -0.5).

CH_4 has significant correlation with NO, NO_2, NOx, SO_2, and RH (r-value> 0.5 for each), and significant negative correlation with O_3, T, and solar radiation (r-value> -0.5).

NMHC has no significant correlation with any of the parameters.

CO has a significant positive correlation with NO, NO_2, NOx, CH_4, SO_2, and RH,(r-value>0.5 for each), and has significant negative relation with O_3 and T (r-value>-0.5). The correlation studies among NO, NO_2, NOx, CH_4, CO, and SO_2 suggest that the dominant sources of air pollution are direct or primary in nature. The major sources of CO are CNG, LPG, and petrol engines. Diesel engines generate a relatively very low amount of CO. Ambient CO emissions always remain within the permissible limit of 5 mg m^{-3} = 5000 μg m^{-3}. Therefore, CO emissions may not be considered low in terms of μg m^{-3} units. The significant positive correlation between CO and NO ($r = 0.72$; p-value < 0.01) shows a common source for both. CNG engines are a main common source for the emission of CO and NO [33]. Pakistan has the highest number of vehicles using CNG fuel [33]. CO produces O_3 through a number of chemical reactions with hydroxyl radicals, and NO in the polluted environment in the presence of sunlight. The dominant sources of CO emissions are two- and four-stroke petrol, CNG, and LPG vehicles. Diesel engines produce only a minute amount of CO emissions [33].

The major source of SO_2 emissions are diesel engines and two-stroke LPG vehicles [33]. SO_2 has a significant positive correlation with NO, NO_2, CH_4, CO, $PM_{2.5}$, WS, and RH (r-value > 0.5 for each), and has significant negative correlation with O_3 and T. The correlation of SO_2 with WS suggests that point sources can be a dominant source for SO_2 emissions. The common source for CO and SO_2 are LPG engines.

$PM_{2.5}$ has significant positive correlation only with SO_2 (r-value > 0.5). The correlation of $PM_{2.5}$ with SO_2 suggests that most of these pollutants originates with fresh emissions from mobile and point sources. Some amount of $PM_{2.5}$ may be produced by chemical conversion of SO_2 into particles. A negative correlation of $PM_{2.5}$ with T has already been reported [34]. Some researchers have reported the conversion of semi-volatile components from particle phase to gas phase at high temperatures [35-38].

Yasar has reported high smoke opacity for most diesel engines, which are a dominant source for $PM_{2.5}$ [33]. Diesel engines are a dominant source for SO_2 and $PM_{2.5}$ emissions, which explains the high correlation between $PM_{2.5}$ and SO_2.

RH has significant positive correlation with NO, CO, SO_2, and WS (r-value> 0.5), and significant negative correlation with O_3 and T (r-value> -0.5). In fact, RH has significant negative correlation with T and has very little correlation with other pollutants. The pollutants may have very minute correlations with WS and RH. In other words, it is difficult to explain the correlation of pollutants with WS and RH in the presence of many other factors as well.

In the winter, the excess amount of ammonia at low temperatures and high relative humidity upturns PM by producing nitrate particles [39, 40]. Temperature has a significant negative correlation with NO, NO_2, CH_4, SO_2, WS, and RH (r-value> -0.5), and has significant positive correlation with solar radiation and O_3 (r-value> 0.5). This explains the production of ozone in the presence of solar radiation at the cost of the precursors of O_3.

Table 5. Ratio analysis based on average emissions and/or ambient data.

Region		CO/NOx	SO_2/NOx
Eastern US	Ambient	4.3	0.94
	Mobiles	8.4	0.05
	Point Sources	0.95	1.8
Pennsylvania Area	Ambient	2.6	1.7
	Mobiles	7.8	0.05
	Point Sources	0.8	2.3
Western US	Ambient	7.3	0.19
	Mobiles	10.5	0.05
	Point Sources	0.18	0.44
Denver Metropolitan area	Ambient	7.3	0.19
	Mobiles	10.5	0.05
	Point Sources	0.18	0.44
Raleigh, NC	Ambient	16.3	0.73
New Delhi, India	Ambient	50	0.58
Lahore (Current Study)	Ambient	16	0.52
	Mobiles	9.71831	0.070423
	Point Sources	0.789474	0.131579

Ratio Analysis

High ratios of CO/NO and low ratios of SO_2/NO indicate that mobile sources are the major source of NO, and point sources are the major source for SO_2 emissions. The production of NOx is associated with high temperatures during fossil fuel burning. Therefore, NOx is usually produced at high temperatures in four-stroke petrol and diesel engines. However, SO_2 is dominantly produced due to high sulfur content in fuel. High sulfur content (0.25-1%) is present in diesel available in Pakistan. Therefore, diesel engines are the major anthropogenic source of SO_2 emissions in Lahore [33]. As NOx is abundantly produced by both 4-stroke petrol engines as well as diesel engines at high temperature, the concentration of NOx usually remains high in Lahore city.

An emission inventory has been provided by [41, 42] for CO, SO_2, and NOx. The data of ratio of CO/NO and CO/SO_2 is given in Table 5, which also provides the ratio analysis of CO by NOx and SO_2 by NOx provided by different studies, such as one in Denver, CO, US [43]; Boulder, CO, US [44]; Raleigh, NC, US [45]; and New Delhi, India [46]. The above studies show a similar trend of ratios of CO/NO and SO_2/NO as do in the current study.

Analysis of Ozone Formation

Ozone is a secondary pollutant. The primary sources for ozone are CO, VOCs, CH_4, NO_2, and solar radiation. A large amount of O_3 has also been produced around high-voltage electric lines. Some countries also claim a high amount of O_3 due to trans-boundary movements. It has been observed that during summers, almost all the NO has been converted to NO_2 by reacting with O_3, being produced by different chemical reactions of CO, CH_4, VOCs, and NO_2 in the presence of sunlight. Therefore, NO concentrations remain almost nil in the presence of high solar radiation during the day in summers. A possible dynamic equilibrium between NO and NO_2 is given in "Eq. 2" [47]:

$$NO + O_3 \leftrightarrow NO_2 + O_2 \quad (2)$$

NO_2 reacts with oxygen in the presence of sunlight to produce O_3 and NO. As the NO concentration is almost nil in day-time in summers, it may be assumed that O_3 has been produced in abundant amounts by different primary sources to keep the reaction forward according to the Le Chatlier principle, i.e., almost all the NO has been converted to NO_2 due to an abundant amount of O_3 being produced by a number of primary sources in the presence of sunlight. Therefore, it can be assumed that O_3 concentration measured at day-time in summers (high solar radiations) is the O_3 that has been produced by sources other than NO_2 or NOx (as the amount of O_3

Table 6. Comparison of dependents through paired sample T-test.

		t	p
Pair 1	NO - O_3	-4.872	.005
Pair 2	NO_2 - O_3	-3.923	.011
Pair 3	NOx - O_3	-4.354	.007
Pair 4	CH_4 - O_3	16.787	.000
Pair 5	$PM_{2.5}$ - O_3	1.811	.130
Pair 6	WS - O_3	-4.977	.004
Pair 7	T - O_3	-3.713	.014
Pair 8	RH - O_3	-3.668	.014
Pair 9	Solar radiation - O_3	15.505	.000

produced by NO_2 has been consumed by NO). Or it may be assumed that whenever the value of NO is negligible, the amount of O_3 produced would be that amount of O_3 that is produced by sources other than NO_2 or NOx.

Another assumption is that sources like VOCs, CO, and CH_4 convert NO to NO_2 and higher oxides of nitrogen. The NO_2 is further photo-lysed to produce O_3. In daytime the value of NO is negligible due to its conversion to NO_2. The value of NO_2 or NOx has been found to be as high as the O_3 value. Therefore, a significant positive correlation is observed between NO_2 and O_3 or between NOx and O_3 in daytime.

To assess the extent of dependence of Ozone on other variables, paired sample t test has been applied on data. The results of paired sample t test are given in Table 6.

The t value of all the precursors of ozone like NOx, CH_4, temperature, and solar radiation is non-zero. The p value of NO, NO_2, NOx, T, and solar radiation are less than or very close to 0.01 (99% confidence level), indicating their significant effect on ozone. For $PM_{2.5}$ p-value is 0.13, indicating no significant dependence of Ozone on $PM_{2.5}$. Although p values for wind speed and RH are close to 0.01, practically RH has no significant relation for ozone, and the dependence of ozone on wind speed depends on wind direction.

Diurnal and Monthly Mean Pattern of Air Quality Parameters

It has been observed that all the primary pollutants like CH_4, NMHC, CO, NO, NO_2, NOx, SO_2, and $PM_{2.5}$ have positive correlations with each other and negative correlations with O_3. The peak value of O_3 has been observed in the daytime due to the presence of high solar radiation, especially in summers. In the absence or reduction of light at night, almost nil or minimum values of O_3 have been observed. The diurnal variations remain the same in every season and all months of the calendar. The value of O_3 has been observed as very high during the summer noon due to high solar radiation. Maximum pollution of primary pollutants has been observed from November to February due to low solar radiation and low photochemical reactions to produce O_3. Fig. 2 shows the diurnal variation of O_3 and other pollutants, while Fig. 3 shows the significant correlation of O_3 with temperature and solar radiation. In Fig. 3, CH_4 levels are divided by 100, NMHC are divided by 10, and CO levels are multiplied by 10 to better elaborate upon their monthly patterns.

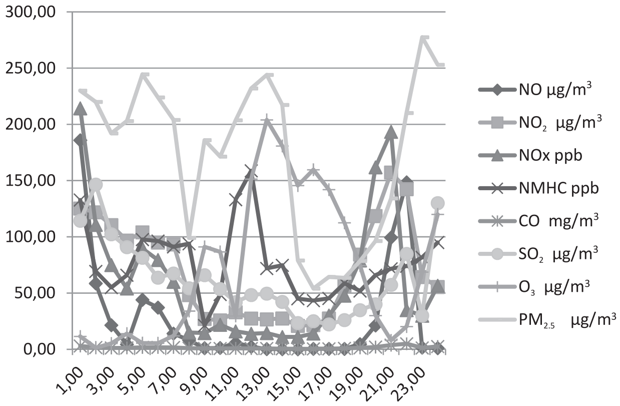

Fig. 2. Diurnal trends of air quality pollutants in the semi-arid region of Lahore.

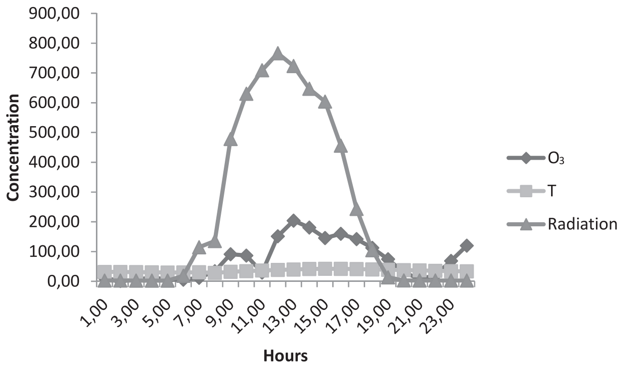

Fig. 3. Diurnal trends of ozone, temperature (T), and solar radiation.

Seasonal Pattern of Ozone and other Air Quality Parameters

There are five different seasons in Lahore. The two main seasons are winter and summer with extreme climatic conditions. As already discussed, O_3 has a significant correlation with temperature (r = 0.7; Table 3). The value of O_3 remains high during summers due to high solar radiation. The concentration of precursors of O_3 remains high during winter mainly due to low solar radians.

The main features of winter in Lahore are:

- Low wind speed,
- Low solar radiation/temperature
- Less precipitation

This favors accumulation and inversion of air pollutants. Therefore, the highest air pollution has been

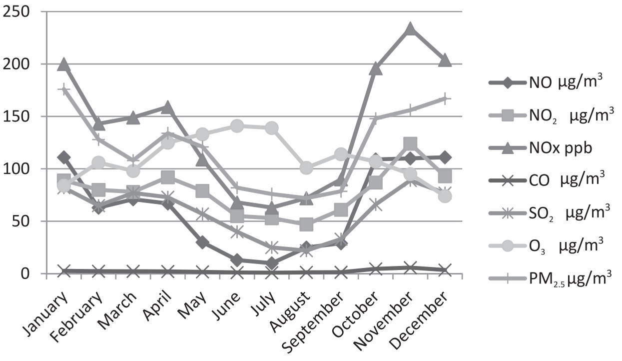

Fig. 4. Seasonal/Monthly patterns of air quality pollutants in the semi-arid region of Lahore.

found from November to February in Lahore as a semi-arid region. But concentrations of secondary O_3 pollutants remain low in winter due to low solar radiation.

Summer is composed of:

- Relatively high wind speed
- High solar radiation/temperature
- Monsoon rains during July and August

All these factors results in the dispersion and washout of air pollutants. But O_3 concentrations remain high during summers due to high solar radiation. Fig. 4 elaborates upon the monthly pattern of O_3 and other pollutants.

Conclusions

We have characterized the ambient air quality for criteria pollutants for Lahore, Pakistan. The annual average concentrations of $PM_{2.5}$ and NO are exceeding the Pak-NEQS. The NEQS for $PM_{2.5}$ needs to be relaxed for a semi-arid region as $PM_{2.5}$ levels are exceeding strict NEQS of 35 µg m-3, even in rural areas around the city.

24 hours and annual Pak-NEQS have not been established for ozone, although its concentration remains too high during summers. Mobile sources are a major source of such high concentrations of NO. The hourly average concentrations of ozone exceed the Pak-NEQS primarily during summer. Carbon monoxide and sulfur dioxide are found to remain in compliance with the Pak-NEQS for the entire calendar year.

The monthly pattern of pollutants show that AQI remains high during winter due to relatively low washing effect (low rain), low wind speed, and high inversion. Moreover, the dominant wind direction from the southeast enables the polluting steel industry to contribute to pollution of Lahore in winter. But ozone levels remain low during winter due to low solar radiation. The diurnal trend of pollutants is similar to the monthly pattern, i.e., AQI remains low in the daytime at high T and solar radiation. The concentration of primary pollutants like NO, NO_2, NOx, CO, SO_2, CH_4, NMHC, and $PM_{2.5}$ remains low in the daytime due to their use as a precursor of O_3 , dispersion effect, and many other factors. The ozone level remains high in the daytime (like in summers) due to high solar radiation and the presence of high concentrations of its precursors.

Ozone has positive correlation with T and solar radiation, and negative correlation with most pollutants like NO, NO_2, NOx, CO, and CH_4. Wind speed, T, and solar radiation have negative correlations with primary pollutants. A wide range of fluctuation in NO concentration has been observed in the presence and absence of solar radiation. Ozone in the presence of solar radiation has a reduction effect for most pollutants other than $PM_{2.5}$ and NMHC.

Correlation studies suggest that the dominant sources of the primary pollutants are fossil fuels, either from mobile sources or point sources. Four-stroke petrol engines are a common source for CO, NO, NO_2, and NOx, which are precursors of O_3. Diesel engines are a major common source for NOx, SO_2, and $PM_{2.5}$. There is a need to reduce sulfur contents in diesel being used in Pakistan. SO_2 emissions mostly remain in compliance with NEQS in Lahore, as most of the vehicles use petrol as fuel. As NOx are abundantly produced by diesel and four-stroke petrol engines, the concentration of NOx mostly remains high in Lahore. Ratio analysis showed that mobile sources are the major sources for NO and point sources are the major source for SO_2 emissions in the city hall area of Lahore.

Ozone is a dreadful pollutant for road traffic for arid and semi-arid areas in summer. There is a need to collect more data of its other primary precursors like VOCs as well.

The population of Lahore has been increasing at a very fast pace. There is a need to stop migration through the provision of health, education, employment, industrial, and fast transport facilities in other cities and remote areas as well.

There is also a need to provide better and more accessible public transport for all the housing societies of Lahore, to promote the use of public transport, and to lessen the use of private vehicles – especially cars.

Acknowledgments

We are thankful to Pak Green Laboratories for provision of instruments for air quality monitoring in Lahore, especially by Mr. Iftekhar and Abdul Hafeez Nasir. We are thankful to Mr. Nadeem, Riaz Ahmad, Ajmal Nadeem, Baber Zaheer, and Ms. Amina Basharat from Punjab EPA for their expert opinions and data provision. Mr. Abdul Khaliq Alvi from Garrison University and Amjid Ali Zafar from the Labor and Human Resource Department are acknowledged for data analysis. Mr. Imran Haider is acknowledged for financial help. Special thanks to Mr. Toshiharu Ochi, JICA expert, for his valuable guidance regarding air pollution monitoring.

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