DEVELOPMENT OF DRIVING CYCLE FOR THE ESTIMATION OF VEHICULAR EXHAUST EMISSIONS AND FUEL CONSUMPTION OF ISLAMABAD

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CERTIFICATE

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MUHAMMAD JAHANZAIB

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Dedicated to……

My beloved parents, siblings &

respected teachers

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List of Abbreviations

WHO	World Health Organization
NEDC	New European Driving Cycle
FTP	Federal Test Procedure
BC	Black Carbon
EFs	Emission Factors
EI	Emission Inventory
GHGs	Greenhouse gases
CO	Carbon Monoxide
CO_2	Carbon dioxide
PM	Particulate matter
NOx	Nitrogen Oxides
HC	Hydrocarbons
DC	Driving Cycle
ICDC	Islamabad City Driving Cycle
FTP	Federal Test Procedure
NEDC	New European Driving Cycle
UEDC	Urban Emissions Drive Cycles
COPERT	Computer Programme to Calculate Emission from Road Transport
CMEM	Comprehensive Modal Emission Model
IVE	International Vehicle Emission Model
MOVES	Motor Vehicle Emission Simulator
AAPE	Average Absolute Potential Error
SAFD	Speed acceleration frequency distribution plot

ABSTRACT

Air pollution is an emerging global and urban environmental issue. Vehicular emissions, containing harmful pollutants, are serious risk to human health and environment. Driving patterns determine the quantity of vehicular emissions per kilometers travelled. Driving pattern of given vehicle in a city is represented by driving cycle which is used by modal models for estimation of vehicular emissions. In this study, a driving cycle was developed for passenger cars in the city of Islamabad. A representative route for the city was identified which included highways, arteries, and streets. Speed-time data was collected along the selected route in both peak and off-peak hours. On-board measurement was method adopted for data collection on highways, whereas on arteritis and streets, chase car method was opted. The collected data was processed for development of driving cycle. The developed cycle showed comparable values of average speed and acceleration with New European Driving Cycle (NEDC), but acceleration and deceleration were observed to be lower. The emission estimation and fuel consumption were calculated by using Comprehensive Modal Emission Model (CMEM) for 4 selected vehicle types. The average emissions for the selected vehicles were; 204.4 g CO_2/km, 2.3 g CO /km, 0.09 g HCs /km, 0.31 g NOx /km emitted and 65.7 g of fuel consumed /km.

Chapter 1

INTRODUCTION

1.1. Background

Air pollution is becoming an emerging issue in Asian region due to its adverse impacts (Kamal et al., 2015) which can be linked to concentration as well as duration of emission and exposure of pollutants (Pouresmaeili et al., 2018). World Health Organization (WHO) reported about 7 million premature deaths due to air pollution depending upon pollutants concentration and time of exposure (WHO, 2014). Depending upon exposure and concentration, outdoor air pollution proves detrimental due to its association with heath related issues (Lelieveld et al., 2015). Rapid urbanization in developing countries, specifically in Asian region, increased the demand of vehicles thus resulting in deterioration of air quality. Less availability of public transport increased the number of private vehicles in these countries, thus increasing energy, traffic congestion and environmental issues (Lu et al., 2017; Zhang and Batterman, 2013; Shan et al., 2016). Vehicular exhaust containing volatile organic compounds, carbon monoxide, nitrogen oxide, carbon dioxide and particulate matter is becoming a serious risk for the people living or moving along road ways (Zhang and Batterman, 2013). World Health Organization (WHO) reported about 60% of the total production of carbon monoxide annually is by human activities (Pouresmaeili et al., 2018). Large buildings in urban areas don’t allow mixing of pollutants, resulting in increase in concentration levels above standard limits (Gately et al., 2017).

1.2. Study Area

Being the capital of Pakistan, Islamabad is located in the Potohar Plateau in the north west of Pakistan having an elevation of 610 meters from sea level with having the latitude of 33.71° North and longitude of 73.1 ° East coordinates, and it is bordered by Margalla hills on one side (North) and plains of an adjunct province (Punjab) on the other side. The Islamabad city is spread over an area of 906 km2 with a reported population exceeding 1.1 million (Qadir et al., 2012; Ulfat et al., 2012). This significance of Islamabad city always invites new dwellers into the city that has resulted in a constant expansion of urban population (Adeel, 2010).

One of the results of such an increase in city population is the huge rise in the transportation flux observed during the past few years (Shah and Shaheen, 2010). Easily availability of vehicles on lease from commercial banks contributed a lot in vehicle population increase which in turn has resulted the air pollution of city (Faiz et al., 2009). Figures for the last five years have also shown an average annual addition of 62,000 vehicles in the city’s overall fleet.

1.3. Need for Developing Driving Cycle for Islamabad

It is well recognized that vehicular emissions rely very much on vehicle speed and acceleration, and driving conditions. Thus, it is important to attain a general understanding of the driving characteristics of Islamabad city. One of the way to classify driving characteristics is to develop a driving cycle by on-road data collection.

The commonly used driving cycles such as New European Driving Cycle (NEDC), Federal Test Procedure (FTP-75) and Artemis Cycle are not representative of the any local region, area, city or even area within the same city. Unavailability of a locally representative driving cycle demands to fill the gap by developing a driving cycle that truly represents the actual conditions of the area for vehicular emissions, fuel consumption etc.

Like NEDC is not efficient for identifying the speed changes, it is also not designed for matching the mode of vehicle operation (percentages of idling, cruising, acceleration, deceleration) and likewise maximum and average speeds, and Artemis cycle is not used for certification of pollutants or fuel consumption. However, car manufacturers use this kind of cycle to better understand real driving conditions and to assess real performances of their vehicles.

While a truly representative driving cycle facilitates in estimating emission rates which are important for estimating harmful air pollutants from vehicular exhaust and emission rates calculation. The use of standard driving cycles cannot give the correct estimation of vehicular emissions is not designed for identifying changes in speed, matching modes of operation, maximum and average speeds.

In this study, we developed an exclusive driving cycle structure covering detailed study of Data collection, route selection, and cycle construction and data analysis methods those are well representative of the Islamabad city road network and driver trip pattern (Driving Pattern). The fraction of road types (Highways, Artries and Streets) covered in a trip will be local to the road network, and this network of Islamabad city is well-developed due to presence of well-established road network, connecting the commercial markets to the residential areas and consisting on Highways, Artries and Streets with covering an area of 906 km2. Hence the standard driving cycles those are commonly used such as NEDC and Artemis Cycle are not appropriate for Islamabad City.

The completed driving cycle, known as Islamabad City Driving Cycle (ICDC), can serve for both legislative and non-legislative purposes. The primary use of the developed driving cycle would be for testing selected test vehicles representative of the typical fleet so as to determine the Fuel Consumption and emissions estimations computed by emissions modeling of passenger car population in Islamabad city.

1.4. Objectives

II. Development of driving cycle for Islamabad city.

III. Emissions and fuel consumption estimation of passenger car population in Islamabad city.

Chapter 2

LITEREATURE REVIEW

2.1. Introduction

Transportation sector heightened the poor urban air quality with on-road vehicles being the dominant contributors to urban air pollution specially in developing countries (Lents and Davis, 2005; Guo et al., 2007; Yu et al., 2009; Zhang et al., 2013; Jing et al., 2017). Increase in number of passenger cars is the outcome of absence of facilities of adequate public transport in developing countries thus resulting in deterioration of air quality (Arun et al., 2017). Several health and environmental problems are outcomes of these vehicular emissions (Shah and Zeeshan, 2016). Including an impact, globally and on local scale as well (Karlsson, 2004), emissions of hazardous air pollutants is mainly because of vehicular emissions (Zhang et al., 2011). Source apportionment studies have usually associated the major share of urban air pollution with the transportation sector (Maykut et al.,2003; Querol et al., 2007). Like, Whitlow et al., 2011 reported in New York City varying linearly concentrations of ultrafine particulate matter (PM) with a traffic flow. Likewise, Wang et al., 2008 and Li et al., 2012 have reported that vehicular emissions have major impact on urban air pollution in the major cities of China, and also a rapid increase in greenhouse gas (GHG) emissions by transportation sector is seen in Europe as well (Pasaoglu et al., 2012).

Around more than 800 million vehicles are estimated on the road today and without involvements, and by 2050 this number is set to expand around 2-3 billion (WRI, 2014). Since in last few decades the speedy increase in the vehicular population also upsurge intentions to address environmental indications and are also been in focus by many countries like China and USA (ADB, 2003; Hao et al.,2007; Vijayaraghavan et al., 2012). Efforts on reducing the immediate adverse effects of these emissions on human health, environment, society and economy are observed (Lents and Davis, 2005; Lents et al., 2007 c; Yu et al., 2009; Sonawane et al., 2012). Understanding of vehicular Emissions and quantification is lacking in spite of their implication specifically in developing countries (Guo et al., 2007). Quantification of these vehicular emissions is restricted due to lack of required resources for the evaluation of existing situation in developing countries.

2.2. Vehicular Emissions

Many toxic air pollutants and Climate forcing pollutants like Greenhouse gases (GHGs), Ozone precursors, Black Carbon (BC) and climate changing pollutant are part of Vehicular exhaust emissions (Shrestha et al., 2013). It is highly challenging to neglect the transport sector from world overall emissions (Achour and Olabi, 2016). In 1998's Kyoto Protocol, Greenhouse Gases (GHGs), carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) are listed as contributor towards global warming (Lee et al., 2013). Pakistan is facing worst effects of climate change, Higher GHGs emissions alter climate globally but changing it first on local and regional scale (Abas et al., 2017). These emissions are recognized as an influential contributor to particulate matter (PM), NOx, CO, and Sulphur oxides (SOx) (Hyder et al., 2006). Around 90% of CO_2 emissions generated from the transportation sector are from vehicle exhaust (Nakata, 2003). Around 82 per cent carbon monoxide (CO), 45 per cent volatile organic compounds (VOCs), 56 per cent nitrogen dioxide (NO_2), 12 per cent lead (Pb), and 5 per cent sulfur dioxide (SO_2) emissions were from transportation sector only in United States. While in China, around 85 per cent CO, 45 per cent VOCs, and 71 per cent nitrogen oxides (NOx), emissions were from vehicular exhaust (Zhang et al., 2013).

2.3. Factors Affecting Vehicular Emissions

Vehicles Operating on the same road can emit around 300 times different emissions from each other (GSSR, 2004). Emission profile of any is vehicle highly dependent Driving Pattern, Local Geography, Vehicle Technology, Type of fuel used, and Climate as well, among all these the driving pattern is highly important for on road emissions estimation (Ntziachristos and Samaras, 2000; Huang et al., 2005). Vehicle technology is also an important aspect for the on-road emissions estimation, and its type can be based on emission control method, engine size, air-fuel management technique, vehicle age and type of fuel used (Lents et al., 2004). Older vehicles when compared with newer one, emits more emissions. In literature it is noticed that the developed countries around 70% emissions emitted only by the around 10% of the higher polluting vehicles (Pokharel et al., 2002; Bishop et al., 2003 a; Bishop et al., 2003 b).

Another factor "driving pattern" that is most important is represented by measuring the speed-time profile of the vehicle (Lents et al., 2004; Yao et al., 2007; Fu et al., 2013). Vehicular emissions are commonly measured by utilizing the driving cycle, however one emission estimation of everywhere or for all cars with one particular driving cycle cannot give the reliable emission estimation, vehicle should be tested differently depending on usage characteristics (Andre et al., 2006). Highly different driving conditions, from the standard cycle for the assessment results cannot present reliable amounts of exhaust emissions and fuel consumption for vehicles (Tamsanya et al., 2012). Vehicles driven in different driving condition show some considerably temporary patterns including acceleration, high speed, cruising etc. giving the considerable amount of exhaust emissions (Davis et al., 2005; Franco et al., 2013). Other local conditions include characteristics of fuel used, road grade, temperate, humidity and also including the traffic preference e.g. public or private also effects on the vehicular exhaust emissions (Tong et al., 2000; Lents et al., 2004 b; Hao et al., 2011).

2.4. Quantifying Vehicular Emissions

Vehicular emission measuring methods include emission profiles and effect of driving operational variables (driving patterns, climatic conditions, fuel types etc.) either under laboratory conditions that are engine and chassis dynamometer tests with controlled conditions or real-world test includes, remote sensing measurements, tunnel studies and on road measurements. Prediction or estimation models developed by the USA and Europe and different Research Institutes are another way of estimations of vehicular emission. The most of the emission models use factors, including driving pattern, vehicle type, climatic conditions, emission standards, to calculate or measure the transportation emissions (Franco et al., 2013; CARB, 2014; EEA, 2014, US-EPA, 2014). Past studies were focused on different fields including, prediction models, measurement technologies, emissions legislations and regulations. There are also different studies that are focused on quantification of vehicular emissions (Yu et al., 2009). Only accurately calculated Emission Factors (EF) can generate reliable emissions inventory and dependency is mostly on the available resources e.g. direct measurement method that is Chassis dynamometer test is simple but it is costly as well (Kim Oanh et al., 2009). Other Direct methods those are remote sensing (Chan et al., 2004), Portable Emission Measurement System (PEMS) (US-EPA, 2005). These methods require sufficient resources for getting the complete real-world conditions. On another hand indirect methods includes emission modeling and it can examine a huge number of vehicles, real world conditions. Generally modeling requires lesser resources and because of this reason the EI of traffic emissions usually this approach is adopted (Davis et al., 2005; Kim Oanh et al., 2012). Emission modeling, cannot give us measurements by using one vehicle only, thus the direct methods are averted (Franco et al., 2013). Modeling can incorporate large number of vehicles, having different fuel types, engine technology, exhaust emission control equipment that can be seen in every vehicle fleet (Kim Oanh et al., 2012). Computer Programme to Calculate Emission from Road Transport (COPERT) model is usually preferred for the EI of vehicles for the confirmation of the European standards in European region (Goyal et al., 2013; EC, 2014). In developing countries, the Emission models like

COPERT, International Vehicle emission model (IVE), MOBILE US EPA Model, have been used and can be. But the factors like faster vehicle deterioration, vehicle technology, driving condition, fuel type, often gives different EFs than those observed in U.S. and Europe (Zhang et al., 2008; Kim Oanh et al., 2012). Furthermore, the models those based on these regions cannot give us the accurate results while using in the other regions (Wang et al., 2008). This requires the use of modified emission factor those fulfil the local conditions. Emission models are usually marked as fuel and travel-based models. While the fuel-based models such as COPERT model can use direct methods for EFs per unit consumed fuel by acquiring from government records and making the fuel-based emission inventory (EEA, 2000; Pokharel et al., 2002). In emission models those are travel based like MOBILE, IVE, EMFAC, and CMEM the EFs and travel stats are connected to generate EI. Research trend can be seen on targeting the joining of transportation and simulation model and emission models for more authentic emission estimation (Yu et al., 2009).

2.5. Importance of Quantifying Vehicular Emissions

Rapid increase in the vehicle population damaged the driving conditions in cities and its mainly because of traffic congestions. This suggested the use of traffic emission projections in air quality management (Smit et al., 2010). In a specific area the measurement of EI and its projections play an important role in the management of air quality. Technology advancement and local factors were suggested by the Noland and Quddus, 2006 for the estimation of EI. The complexity and extensiveness of emission models is raised over time (Smit et al., 2009). The increase in the vehicle population justifies this complexity, pollutants and emissions, and fuel types being considered in emission models. Globally significant researches have been conducted to study the effect of policies to minimize the emissions from on road vehicles (Lumbreras et al., 2008). For example, different traffic control plans and emissions depending upon them are studied by (Seika et al. 1998). The non-motorized transport cost benefit analysis is produced by Sælensminde, 2004. (Hao et al., 2006) determined different factors for reducing vehicular emissions, and (Kim Oanh et al., 2012) and (Shrestha et al., 2013) evaluated interest of improved technology implementation and its potential impact on global warming.

2.6. Driving Cycle

Increased usage of vehicles and urban logistics resulted in increased traffic jams on roads requiring optimization and restraining of transport frequencies. Several solutions have been proposed to address this issue which includes using technologies with environmental friendly applications, imposing regulations, changing travel habits and transport policies, imposing environmental taxes etc. Reducing air emissions by reduction in traffic on roads is not supposed to be an optimal solution of the problem as simultaneous dealing with public and private transport is almost impossible in large cities (Knez et al., 2014). Some researchers established tools for predicting total emissions by working on estimation of vehicular emissions by different modeling approaches (Esteves-Booth et al., 2002). Prediction of emissions trough modeling also has its drawbacks like absence of availability of data on emissions for all vehicles types and their operational modes. The best solution to the above mentioned problem is developing a driving cycle describing driving patterns and forecasting vehicular emissions accurately. Traffic conditions and driving patterns are the major factors contributing the emissions from vehicles (Knez et al., 2014), which vary from one location to another thus making each driving cycle unique (Arun et al., 2017).

Driving cycles utilizes a representative speed-time profile of a specific area to describe driving pattern and forecasting vehicular emissions by using speed and acceleration of vehicles. These are used conclusively in calculating energy consumption and traffic impact assessment in addition to estimating vehicular emissions (Pouresmaeili et al., 2018). Three basic steps towards the generation of driving cycle are route selection followed by data collection and cycle construction (Pouresmaeili et al., 2018; Arun et al., 2017). Route selection, as a first step, focused on choosing a road type (arterials, sub-arterial, expressway etc.) representative of actual road conditions of the specific area. Data collection involve per second measurement of speed of vehicle for speed-time profile by on-board measurements or chase-car method. Driving cycle construction involves splitting the data into micro-trips first (Arun et al., 2017). Micro-trips are then usually combined in a random way with the duration ranged from 1000 to 1400 seconds (Pouresmaeili et al., 2018). The duration of these micro-trips should be the representative of real-world driving practices and also aid in testing vehicular emission (Arun et al., 2017).

Standard driving cycles (European driving Cycle and US FTP), fail to represent driving patterns and behaviors of worldwide locations, thus requiring the need of separate driving cycles of each location. Driving cycle, defined by vehicular speed

(Knez et al., 2014), idling, cruising, deceleration and acceleration (Arun et al., 2017), represents driving practices and conditions within the region for which it was designed. As driving practices and conditions vary from one region to another (Knez et al., 2014) due to difference in meteorological conditions, and road structure (Gately et al., 2017). Thus driving cycle designed for one particular region can't be representative of the conditions of another region (Knez et al., 2014). Developing a driving cycle offers several advantages like traffic simulation, designing and evaluation of performance of vehicles, delay calculations, traffic control etc. (Pouresmaeili et al., 2018; Arun et al., 2017). Also driving cycles are commonly used in many countries as a standard emission test of new vehicles before their launching (Davari et al., 2017).

2.5. Comprehensive Modal Emission Model (CMEM)

Comprehensive modal emission models targeting on complex details of traffic dynamics and it also consider fluctuation in emission rates because of different driving modes. Few other emission models such as, mentioned earlier Comprehensive Modal Emission Model (CMEM) (Barth et al., 2000), and VT-Micro (Ahn et al., 1999) for the emissions rates calculations uses the second by second vehicular speed data. In addition, these emission models used to derive acceleration and percentage time spent in each driving mode. On the other hand, few other models few other emission model uses average speed of vehicle, and are unable to consider the change in speed on small scale and different other driving modes by traffic congestion. Higher ambiguity can be seen by such type of models for emission estimation, like (eg. MOBILE) (Adak et al., 2016).

Chapter 3

METHODOLOGY

DC In this study passenger car is developed as due to prevailing traffic regulations, heavy-duty vehicle entrance is restricted in the city and passenger cars are main component of the vehicular fleet. Detailed methodology of each step is given as following.

3.1. Route Selection

Route selection is an important aspect of the on-road speed-time profile data collection for DC.

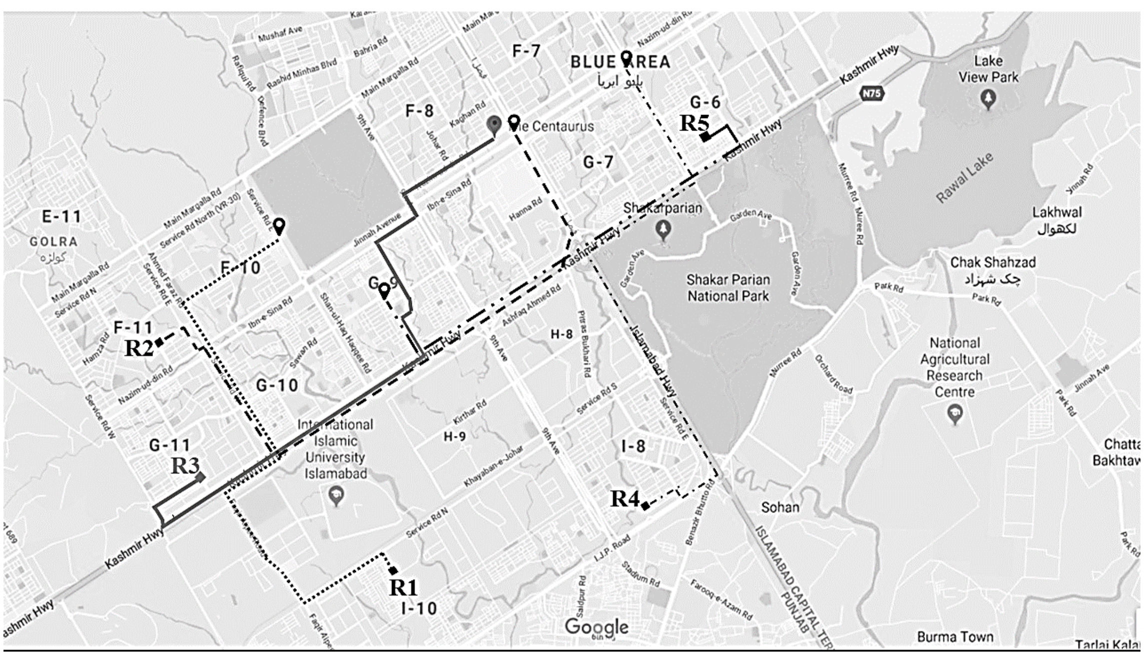

Figure 3.1 Finally selected route (R_3) with initially considered other 4 candidate routes

As selected route must be representative of all variation of data expected in the city as it is not feasible to collect the speed-time profile for all road networks. Due to unavailability of traffic flow data of the city roads, initially, five different routes were selected based on observations of the traffic flows and considering the land use patterns in the city. Selected routes are shown in Figure 3.1. Islamabad is a well-planned city with clearly separating the residential areas from commercial ones, connected together with precisely designed road network of streets, arteries and highways. Initially selected routes involved all three types of the roads, commercial areas, residential areas and one major highway of the city. A questionnaire-based survey was conducted among the commuters (N=1000) on major refueling stations situated on initially selected five routes, inquiring them about their daily travelling route as well as a length of a typical trip and, based on the survey results, it was ensured that the final selected route represents a typical pathway of an average office employee/ consumer travelling from home to work/shopping mall in the city. Length of the finally selected rout was 10.5 km.

3.2. Speed-time Data Collection

The on-road speed-time profile data collection was done from August to September 2016. For representation of different driving conditions at different traffic congestion scenarios, data was collected for both the peak and off-peak hours and also for weekdays and weekends. Details of data collection timing has been given in Table 3.1.

Two different methods have been previously used for speed-time data collection; i- Chase car method and ii- instrumented car method. In chase car method a target vehicle is selected randomly and is followed by a vehicle, instrumented and capable of monitoring speed-time data at an appropriate distance to mimic the acceleration/deceleration patterns and rates of the target vehicle. This method has been used in Bangkok (Tamsanya et al., 2009), Hongkong (Tong et al., 1999). Edinberg (Saleh et al., 2009), Pune (Kamble et al., 2009) and Sydney(Kent et al., 1978). Chase car method is appreciated as the driver of the target vehicle remains unaware of his/her driving pattern being recorded and hence the driving behavior is unbiased.

Table 3.1 Details of the data collection timing with reasons

No.	Data collection Interval	Reasoning
1	Weekdays (Monday - Friday)	
1.1	Morning peak hours (0730 – 0930 hr)	To represent the morning traffic peak hors flow pattern which includes the activity due to school going kids.
1.2	Lull hours (1000 – 1500 hr)	To incorporate the traffic patterns variation during lull hours in sampling
1.3	Evening peak hours (1600 – 1900 hr)	Evening peak hours are different from morning peak hours as traffic due to school activities is not included due to school timings
2	Weekends (Saturday & Sunday)	
2.1	Normal activity hours (0900 – 2100 hr)	To incorporate the variance in traffic flow characteristics on weekends in the sampled data

However, data collection by this method essentially involves the biases incorporated by the driving behavior of the chasing vehicle. On the other hand, in instrumented car method, the target vehicle itself is instrumented to record its speed-time data. This approach has previously been used for Australian Urban Emissions Drive Cycles (UEDC) (Brown et al., 1999), Dublin driving cycle (Achour and Olabi, 2016) and Delhi driving cycle. Although, this method collects exact data of the target vehicle, possibility of biased driving behavior is there in this method as the driver becomes conscious of the instruments installed onboard. In this study, speed-time data for the highway part of the route was collected by instrumented car method. However, the used cars were selected randomly by hitchhiking and a small keychain sized GPS data logger (DG-200 GlobalSat) was used to record time stamped location data while the driver was unaware of data collection during the trip. Thus, biased driving behavior was minimized and maximum variation was incorporated in the collected data as the target cars were picked up randomly, each having different driver. The data logger gives reliable and continuous speed of vehicles for every second along with the altitude (slope) information. Since the highway segment of the selected route was a single straight road, hitch hiking was a practical option for data collection. However, the streets and arteries segments of the route were more complex hence hitchhiking was not considered as a practical option. Rather, chase-car method was used for streets and arteries. For more precise chase in congested traffic situations, an instrumented motor bike was used as chase vehicle on arteries and streets, rather than a car. To capture the maximum variation, 30 trips of the selected route were made for data collection.

3.3. Data Processing and Cycle Development Method

Details of collected data processing for DC development is presented in Figure 3.2 Extensive literature review (Arun et al., 2017; Ho et al., 2014; Pouresmaeili et al., 2018; Tong et al., 2011, 1999)was conducted to select parameters describing the driving characteristics. The parameters are listed below;

- Average speed of trips (V_a) in km/hr;
- Average running speed (V_r) in km/hr, (excluding idling time);
- Average acceleration of all acceleration phases (a) in m/s^2;
- Average deceleration of all deceleration phases (d) in m/s^2;
- Mean length of a driving period (c) in seconds;
- Percentage time of driving Modes-Idling (Pi);
- Percentage time of driving Modes-Cruising (Pc);
- Percentage time of driving Modes-Acceleration (Pa);
- Percentage time of driving Modes-Deceleration (Pd);
- Root mean square acceleration (RMS).

Table 3.2 Equations used for calculation of assessment parameters

No.	Equation	Unit	Formula
1	Average Speed (V_a)	Km/hr	$Va = (1/T) \int_0^T v(t)dt$
2	Average running speed (V_r)	Km/hr	$V_r = (1 / T) \int_0^T v(t)\, dt\,, \quad v(t) > 0$
3	Average acceleration of all acceleration phases (a)	m/s^2	$a = (1/T) \int_0^T a(t)dt\,, \quad v(t) \geq 3km/h, \quad a(t) \geq 0.3m/s^2$
4	Average deceleration of all deceleration phases (d)	m/s^2	$d = (1/T) \int_0^T a(t)dt, \quad v(t) \geq 3\, km/h, \quad a(t) < -0.15m/s^2$
5	Percentage time of Idling (P_i)	-	$Pi, \quad v(t) < 3\ km/h$
6	Percentage time of Cruising (P_c)	-	$Pc, \quad v(t) \geq 3\ km/h\,, \quad -0.15 \leq a(t) < 0.3\, m\, /\, s^2$
7	Percentage time of acceleration (P_a)	-	$Pa, \quad v(t) \geq 3\ km/h\,, \quad a(t) \geq 0.3\, m/s^2$
8	Percentage time of deceleration (P_d)	-	$Pd, \quad v(t) \geq 3\ km/h\,, \quad a(t) < -0.15\, m/s^2$
9	Root mean square (RMS)	m/s^2	$RMS = \sqrt{(1/T) \int_0^T [a(t)]^2\, dt,}\ \ v(t) \geq 3\ km/h\,,\ a(t) \geq 0.3\, m/s^2$

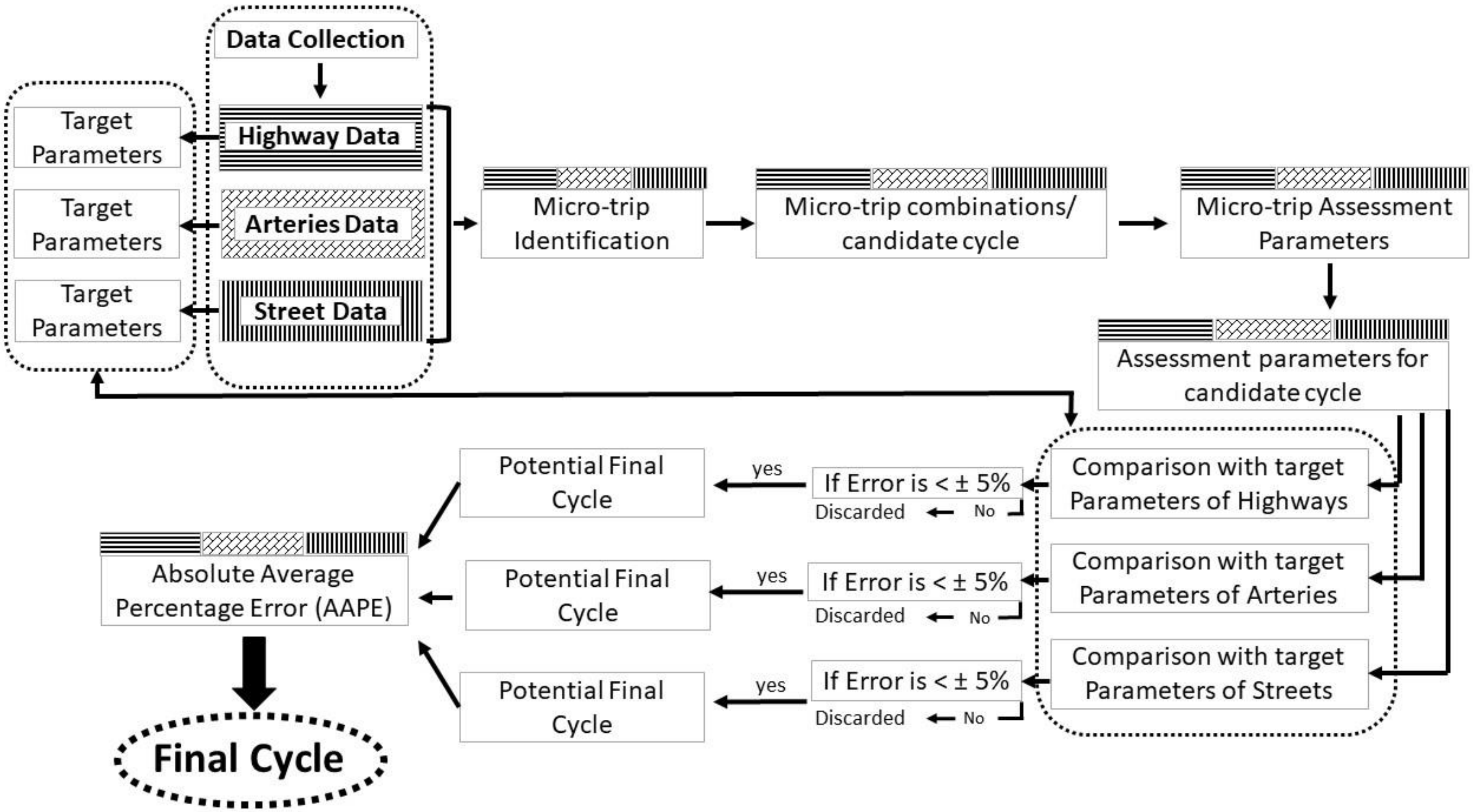

Figure 3.2 overall driving cycle development process flow diagram

Collected data was processed in software package MATLAB R2016a (The MathWorks, Inc.). Detailed methodology for data processing has been reported in the literature (Arun et al., 2017; Ho et al., 2014; Tong et al., 2011). Assessment parameters were calculated for all trips of three types of road (here onward called 'target parameters'). Micro-trips were identified among data collected during all trips of three road types. Assessment parameters were calculated for each micro-trip. Micro-trips were randomly combined to form a candidate cycle for three types of roads. Assessment parameters were calculated for each candidate cycle and compared with target parameters. If the error for all assessment parameters was found to be less than ±5%, the candidate cycle was selected as 'potential DC'. If error was higher, it was rejected. A list of potential DCs was obtained for each road type and DC with over all least average absolute percentage error (AAPE) was selected.

Chapter 4

RESULTS AND DISCUSSION

4.1. Driving Cycle

In total, 30 trips of each of the road types were made for speed-time data collection. After processing, 91 micro trips were identified in data collected for highways, 102 for arteries and 51 for streets, as there were no signals present in streets. Combined for all road types, about 15000 speed-time data were collected. Speed acceleration frequency distribution plot (SAFD), which represents the visual information of driving pattern, is shown in Figure 4.1 whereas normal distribution of speed acceleration is given in Table 4.1.

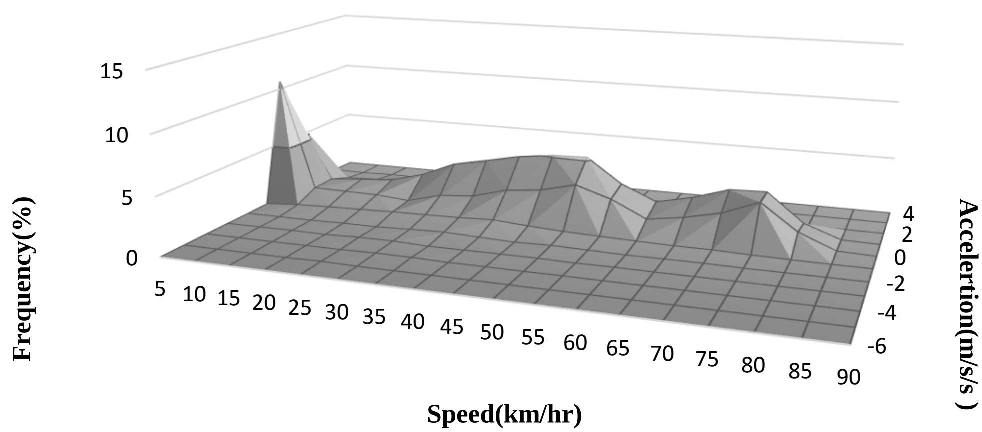

Figure 4.1 Speed-acceleration frequency distribution for all three types of roads

Table 4.1 Normal distribution of speed-acceleration data for all road types (streets, arteries and highways)

Speed (km/h)	Acceleration (m/s/s)										Total
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	
5	0.00	0.00	0.00	0.00	0.00	0.02	10.66	6.10	0.44	0.06	0.00	17.28
10	0.00	0.00	0.00	0.00	0.01	0.22	0.98	0.99	0.30	0.01	0.00	2.51
15	0.00	0.00	0.00	0.02	0.01	0.33	0.93	1.25	0.42	0.09	0.00	3.05
20	0.00	0.00	0.02	0.00	0.06	0.41	0.89	1.48	0.73	0.06	0.00	3.65
25	0.00	0.05	0.02	0.09	0.07	0.50	0.67	2.40	0.33	0.01	0.00	4.08
30	0.00	0.00	0.07	0.11	0.17	0.52	1.44	3.53	0.46	0.02	0.00	6.32
35	0.00	0.00	0.06	0.00	0.26	0.61	1.68	4.12	0.34	0.00	0.00	7.08
40	0.00	0.01	0.00	0.02	0.15	0.73	2.52	4.75	0.22	0.00	0.00	8.38
45	0.00	0.00	0.02	0.04	0.05	0.52	2.83	5.12	0.13	0.00	0.00	8.71
50	0.00	0.00	0.00	0.04	0.12	0.36	3.58	5.22	0.03	0.00	0.00	9.35
55	0.00	0.00	0.02	0.00	0.07	0.27	2.61	3.12	0.05	0.00	0.00	6.14
60	0.00	0.00	0.00	0.02	0.01	0.20	1.16	1.81	0.02	0.00	0.00	3.22
65	0.00	0.00	0.00	0.00	0.03	0.14	1.64	2.50	0.02	0.00	0.00	4.32
70	0.00	0.00	0.01	0.01	0.04	0.14	2.33	3.48	0.01	0.00	0.00	6.01
75	0.00	0.00	0.00	0.01	0.00	0.05	3.56	3.58	0.00	0.00	0.00	7.20
80	0.00	0.00	0.00	0.00	0.00	0.02	1.36	1.16	0.00	0.00	0.00	2.53
85	0.00	0.00	0.00	0.01	0.00	0.00	0.09	0.06	0.00	0.00	0.00	0.16
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	0.05	0.20	0.36	1.05	5.04	38.93	50.65	3.52	0.25	0.00	100.00

The resolution of the SAFD was 5km/hr and 1m/s^2. Speed of the passenger cars varied from 0 to 85 km/hr with acceleration range of -6 to 4 m/s^2. As Figure 4.1 shows, the speed occurrences were uniformly spread over total speed range with significant fraction of idling (when both, speed and acceleration were insignificant) as there were 8 signals present on selected route. The peak between 60 to 85 km/hr typically shows the higher speed recorded over highway part of the route whereas the other significant peak (30 to 60km/hr) showed speed variation recorded mainly on arteries with some overlapping of highways. The acceleration/ deceleration was slightly more observed on arteries than highways as arteries were linked with streets, reducing probability of cruising conditions. Table 4.2 shows the values of target parameters calculated for the three types of roads. Maximum speed was observed for highways, followed by arteries and streets with acceleration/deceleration in reverse order for three road types, respectively.

Table 4.2 Target parameters for three road types of Islamabad

	V_a	V_r	a	d	Pi (%)	Pc (%)	Pa (%)	Pd (%)	RMS
Highways	51.53	57.25	0.12	-0.16	11.32	53.64	16.30	18.76	0.40
Arteries	30.25	37.95	0.15	-0.19	20.78	34.17	22.23	22.89	0.44
Streets	24.33	24.33	0.28	-0.33	7.87	26.23	36.37	29.53	0.68

Figure 4.2 shows the developed ICDC having large variations of speed over time. Total length of the cycle is 1307s with first 125 seconds representing the driving pattern in streets, having lower velocities. Overall, the cycle showed multiple idling occurrences depicting the presence of signalized intersection. Deceleration and accelerations are visible before and after each of the intersection. Maximum speed of ICDC is 76.5km/hr with an average speed of 38.1km/hr.

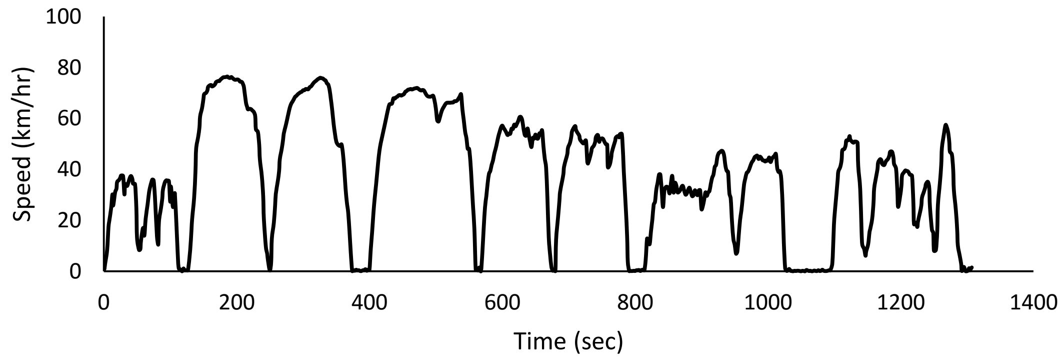

Figure 4.2 Islamabad City Driving Cycle (ICDC)

Table 4.3 compares ICDC with other international driving cycles. Although average speed and average running speed of the ICDC was closer to NEDC, the acceleration and deceleration values were found to be much low and total percentage of cruising mode was high as compared to other driving cycles. Table 4.3 depicts that none of the international developed cycles can be precisely used for passenger car driving pattern in Islamabad.

Table 4.3 Comparison of ICDC with international driving cycles

	V_a	V_r	a	d	Pi (%)	Pc (%)	Pa (%)	Pd (%)	RMS
ICDC	38.36	44.48	0.16	-0.20	14.33	41.77	21.49	22.40	0.60
NEDC	33.60	42.24	0.53	-0.72	20.42	38.81	23.56	17.29	0.14
FTP-72	31.60	36.60	0.43	-0.46	13.81	18.04	36.96	31.19	0.20
ARTEMIS	17.70	22.29	0.53	-0.57	20.75	9.57	20.75	33.74	0.29

Table 4.4 Pollutant Emissions for ICDC and NEDC using CMEM

Vehicle Type	ICDC					NEDC				
	Fuel (g/km)	CO2 (g/km)	CO (g/km)	HC (g/km)	Nox (g/km)	Fuel (g/km)	CO2 (g/km)	CO (g/km)	HC (g/km)	Nox (g/km)
Passenger Car 1	63.7	199.3	1.7	0.056	0.347	70.5	220.3	2.0	0.090	0.181
Passenger Car 2	64.2	200.1	2.0	0.063	0.319	76.3	238.5	2.1	0.103	0.147
Passenger Car 3	64.8	201.0	2.6	0.106	0.351	69.5	218.8	1.0	0.046	0.214
Passenger Car 4	70.0	217.2	2.9	0.120	0.231	67.2	212.1	0.5	0.048	0.173
Average	**65.7**	**204.4**	**2.3**	**0.086**	**0.312**	**70.9**	**222.4**	**1.4**	**0.072**	**0.179**

Selected 4 car types emission estimations and fuel consumption calculated by using the Comprehensive Modal Emission Model (CMEM). NEDC and Developed driving cycle for this city ICDC were used as the speed time profile (vehicle activity). The comparison was conducted for the both of the cycles for emission estimations and fuel consumption. Pollutants emitted for both cycle NEDC and ICDC and the averages of all selected 4 types of vehicles are presented in Table . NEDC values for Fuel (7.9%) and CO2 (8.8%) were observed higher than respective ICDC values. While the NEDC values for CO (39%), HC (16.2%), and NOx (42.6%) were observed lesser than the respective values of ICDC.

Chapter 5

CONCLUSIONS & RECOMMENDATIONS

5.1. CONCLUSIONS

- ICDC is significantly different from other existing international driving cycles like NEDC, FTP, and ARTEMIS.
- ICDC is significantly different from mostly used international cycle that is NEDC in average speed, maximum speed and intermittent stops as well.
- As well as NEDC is not designed for the fuel and emission estimations so, ICDC development gives us more realistic estimations.
- The 8 no of signals were observed in the path of ICDC.
- Travel delays were also greater than other Asian cities like Hanoi, Singapore, Chennai and Mashhad.
- Last 5 years data from vehicle registration department showed an average addition of 62,000 vehicles each year to city's overall Islamabad vehicle fleet.
- Passenger cars had the largest vehicle share in overall vehicle fleet of the city.
- With respect to road types, more traffic congestion was observed at arterials and secondly on highways and least on the streets portion.
- Higher velocity was observed at highways, followed by the arteries and the streets where the average velocity at highways is 51.53 km/hr.

- Likewise, higher emissions were observed during at the arterial roads because of congestion and travel delays.
- Results showed that 204.4 g/km of CO_2, 2.3 g/km of CO, 0.086 g/km of HCs and 0.312 g/km of NOx were emitted on an average of all four selected types of vehicle in the fleet on route of ICDC.

5.2. RECOMMENDATIONS

Research level suggestions for future work in this area include:

- City and Region-specific driving cycles should be developed for better emission and fuel consumption estimation.
- Vehicle population control measures should be adopted by promoting public transport for positive impact on the air quality of the city.
- Improved driving conditions (higher average speed, high engine stress mode etc.) can be assumed to assess their potential impact on the local emissions.
- Improved traffic management, appropriate signal installation and signal wait times can also reduce the emission rates.
- HTVs like Buses and trucks can also be included in future to study their emission share.

Policy level interference can be formed to reduce vehicular emissions such as:

- Proper Inspection & Maintenance (I/M) programs for vehicles.
- Vehicle population control measures.
- Malleable and/or un-parallel working hours to escape from usual rush hour congestion.

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