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Development of Driving Cycle for Passenger Cars and Estimation of Vehicular Exhaust Emission Factors

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Abstract

Driving pattern of the given vehicle in a city is represented by the 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 city was identified which included parts of highway, arteries, and streets. Speed-time data was collected along the selected route in both peak and off-peak hours. The on-board measurement method was adopted for data collection on highways, whereas on arteritis and streets, chase car method has opted for data collection. 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 the 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 NO_x /km emitted, and 65.7 g of fuel consumed /km. The developed cycle showed higher fuel consumption and CO_2 emissions /km traveled than NEDC for all 4 passenger car types. However, HCs, CO, and NO_x emissions were lower. The developed driving cycle can be used for estimation of the emissions from passenger cars in the city and this information can be useful for future emission projections and policy making.

Keywords: Driving Cycle; CMEM; Emission Estimation; Driving Patterns

Introduction

Air pollution is serious and an emerging global issue due to its adverse impacts on human health and the environment [1,2]. Vehicular exhaust containing volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO$_x$) and particulate matter (PM) is becoming a serious risk for the people living in urban areas [3]. World Health Organization (WHO) reported about 7 million premature deaths each year due to exposure to air pollution (WHO, 2014). Depending upon the type of pollutants, exposure duration, and concentration, outdoor air pollution has been linked with lung cancer, stroke mortality [4] cardiovascular diseases, chronic respiratory diseases [5,6] asthma, chronic obstructive pulmonary diseases (COPD), and cancers including lung, cervical and brain cancers [7]. Traffic-related air pollution has also been reported to be associated with diabetes and nervous system diseases [8,9]. Rapid urbanization in developing countries increased the road transportation demand thus resulting in deterioration of air quality. Source apportionment studies have identified the transportation sector as a significant contributor to urban air pollution [10-12]. Hence quantification of vehicular emissions is an important aspect of urban air quality management, which has historically been achieved by the use of emission models. With the increasing vehicular population and thus the emissions, the models also have been more comprehensive and realistic.

Before the 1980s, the emission calculation models had the capability to calculate emissions of fewer pollutants, generally, assuming hot engine running conditions (ignoring cold startups). However, more recently developed models not only cover a large number of engine types/sizes, fuel types and can calculate emissions of greenhouse gasses and air pollutants but also take driving patterns as input for emission calculation (and thus called 'modal models') [13]. Modal models, e.g. Comprehensive Modal Emission Model (CMEM) and Virginia Tech Microscopic (VT-Micro) Model, use second by the second variation of the vehicular speed for emission estimation against the average vehicular speed used by others (e.g. MOBILE) and thus produce emission estimates with lesser uncertainties as traffic conditions and driving patterns are the major factors affecting vehicular emissions [14]. Previously, CMEM has been used for the estimation of vehicular emission factors and specific fuel consumption (g/km) in various cities, including Chennai [15], Dhanbad [16], Singapore [17] and Beijing [18]. The CMEM model is also stands out having no geographical limitations for estimation.

One common technique to identify and quantify the driving patterns in a city are by developing its driving cycles for different vehicle categories. Driving cycles utilize a representative speed-time profile of a specific area to describe the driving patterns and consequently, forecast vehicular emissions accurately by using the speed and acceleration of vehicles [19]. Generation of driving the cycle is mainly based on route selection followed by data collection and processing [20]. Standard driving cycles e.g. European Driving Cycle (EDC), New European Driving Cycle (NEDC), and US Federal Test Procedure (FTP) has been reported to fail in representing driving patterns of worldwide locations, as driving practices and conditions, vary from one region to another [13] depending on multiple factors including meteorological conditions, vehicular activities, and structure/capacity of roads [21]. Hence the development of location-specific driving cycles is necessary.

This study is focused on developing a driving cycle for passenger cars in Islamabad city. Population of Islamabad (33.71° North, 73.1° East and an altitude of 610m above sea level) is reported to be exceeding 1.1 million [22,23] and it covers an area of 906 km², having a well-planned spread of commercial and residential areas which are well connected with each other having a network of highways, arteries, and streets. South Asian countries like Pakistan have seen urbanization on a mega-scale in recent years (IGES,2005; [24] bringing more vehicles on roads [25]. According to the Excise and Taxation Department of Islamabad city, the number of vehicles registered in the city has increased from 89917 in 2000 to 759886 in 2016 having more than 65% share of passenger cars, including private and commercial vehicles. This growth in the vehicular fleet of the city has resulted in significantly increased pollutant emissions [26] and is reported to cause higher prevailing pollutant concentrations in the ambient air [27]. Hence the commonly used standard driving cycles such as NEDC and Artemis Cycle may not be representative of Islamabad City. The developed driving cycle, known as Islamabad City Driving Cycle (ICDC), can serve both legislative and non-legislative purposes. The driving cycle has also been used for the estimation of passenger car emissions in the city by using CMEM.

Methodology

Route selection, data collection, and data processing are the three major steps for the development of a driving cycle. In this study ICDC is developed for passenger cars as due to prevailing traffic regulations, heavy-duty vehicle entrance is restricted in the city and passenger cars are the main component of the vehicular fleet. The detailed methodology of each step is given as following.

Routes Selection

Route selection is an important aspect of the on-road speed-time profile data collection for the driving cycle. The 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 of the road networks.
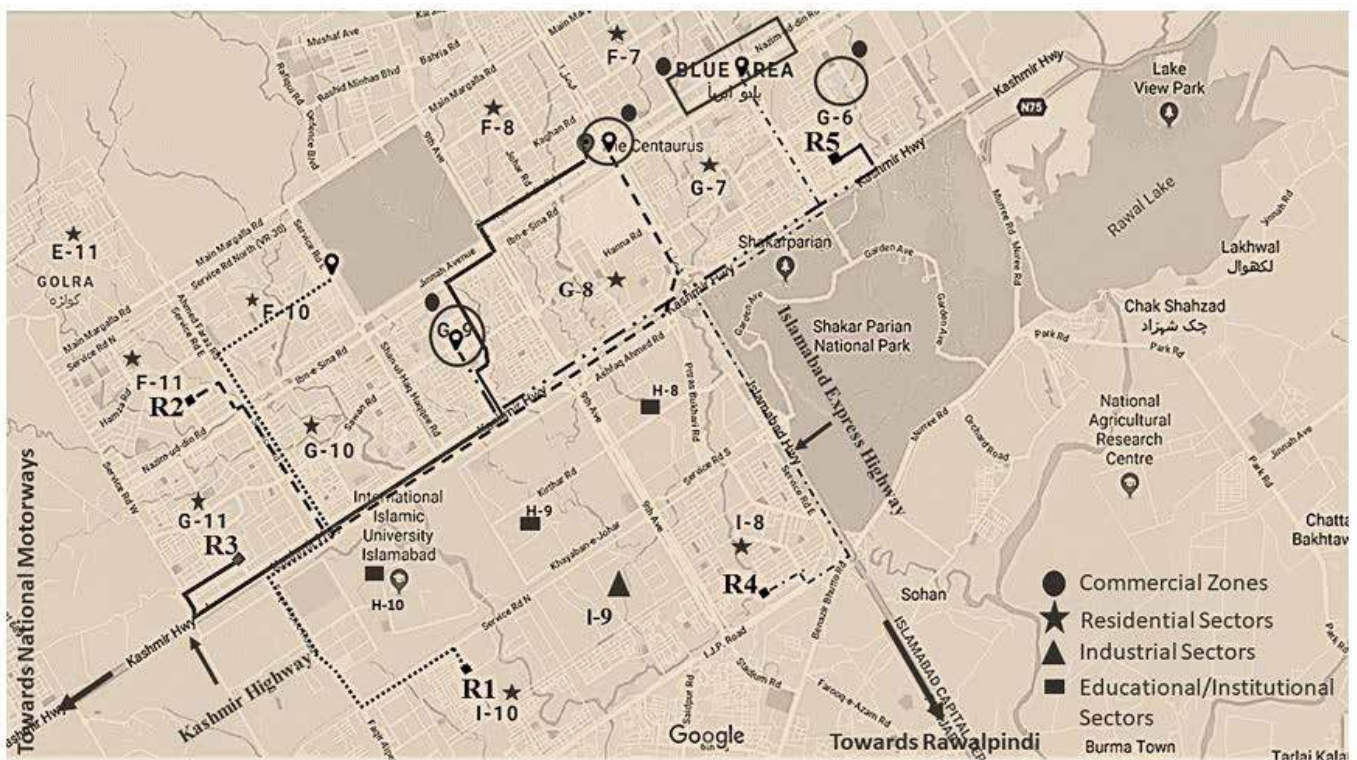

Figure 1: Land use in Islamabad City, candidate routes and the finally selected route (R3)

Due to the unavailability of traffic flow data of the city roads, initially, five different routes were selected based on discussions with traffic police officials and visual observations of the traffic flows and considering the land use patterns in the city. Selected routes are shown in Figure 1. Unlike other cities of developing countries, Islamabad is well-planned with clear separations between residential and commercial areas, connected together with a well-planned road network of streets, arteries, and highways. Initially selected routes involved all three types of roads, commercial areas, residential areas, and one major highway of the city. A questionnaire-based survey was conducted among the commuters on major refueling stations along the initially selected five routes, inquiring them about their daily traveling route as well as a length of a typical trip. Based on the survey results, it was ensured that the final selected route represents a typical pathway of an average office employee/ consumer traveling from home to work/shopping mall in the city. Length of the finally selected the route was 10.5 km which includes all mentioned road types of Islamabad city (Figure 1).

Speed-time data collection

On-road speed-time profile data collection was done from August to September 2020. For representation of various 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 have been given in Table S1.

Two different methods have been previously used for speed-time data collection; i- chase car method and ii- instrumented car method. In the former, 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 [26], Hongkong [29], Edinberg [30], Pune [31] and Sydney [32]. 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 remains unbiased. 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) [33], Dublin driving cycle [34] and Delhi driving cycle [35]. Although this method collects exact data of the target vehicle, the possibility of biased driving behavior is there as the driver becomes conscious of the instruments installed onboard. In this study, speed-time data collection for the highway portion was done by the 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 possible variation was incorporated in the collected data as the target cars were picked up randomly, each having a different driver. The data logger recorded the 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, hitchhiking was a practical option for data collection. However, the streets and arteries segments of the route were more complex hence hitchhiking was not considered a practical option. Rather, the chase-car method was used for streets and arteries. For more precise chase in congested traffic situations, an instrumented motorbike was used as a 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.

Data processing and cycle development method

Detail of the data processing for driving cycle development is presented in Figure 2. Extensive literature review [15,17,20,29,36] was conducted to select parameters describing the driving characteristics. The parameters and their respective formulas are given in Table 1.

Data were processed in a software package MATLAB R2016a (The MathWorks, Inc.). Detailed methodology for data processing has been reported in the literature [15,17,36] Assessment parameters were calculated for all trips of the three types of road (here onward called 'target parameters'). Micro-trips were identified among the data collected. 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 driving cycle'. If an error was higher, it was rejected. A list of potential driving cycles was obtained for each road type and the driving cycle with the overall least average absolute percentage error (AAPE) was selected as the final driving cycle.
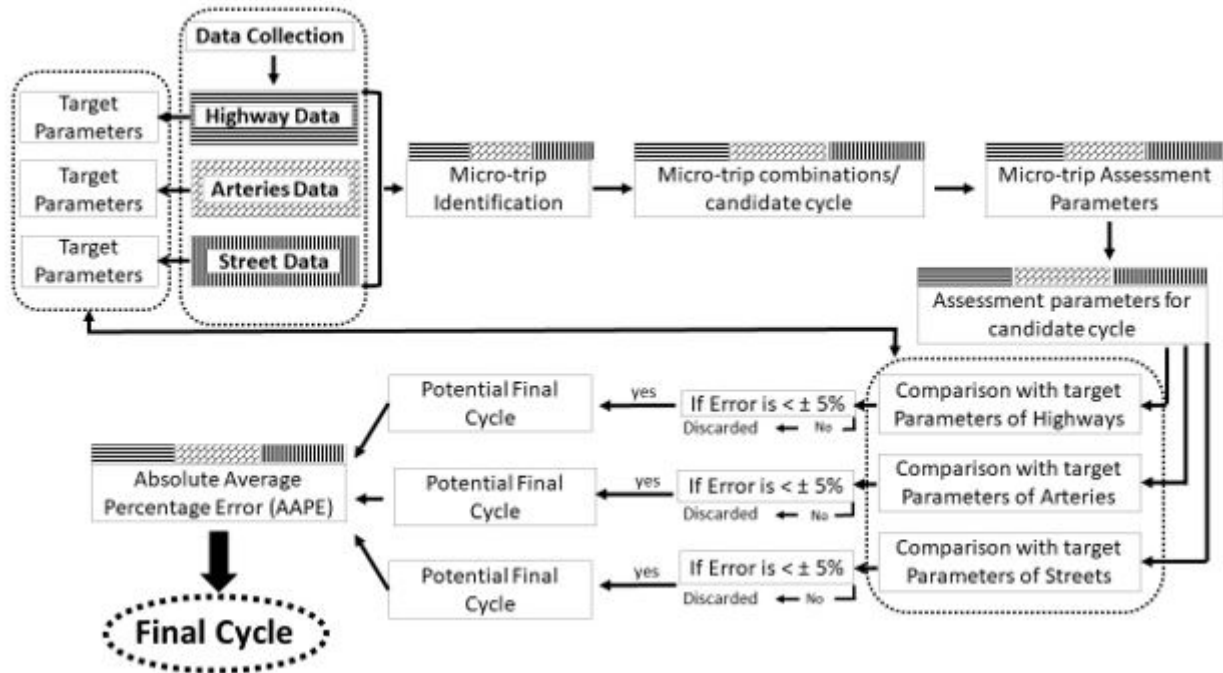
Figure 2: Overall driving cycle development process flow diagram

No.	Equation	Unit	Formula
1	Average Speed (V_a)	Km/hr	$V_a = (1/T)\int_0^T v(t)dt$
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/s²	$a = (1/T)\int_0^T a(t)dt, \quad v(t) \geq 3km/h, \quad a(t) \geq 0.3m/s^2$
4	Average deceleration of all deceleration phases (d)	m/s²	$d = (1/T)\int_0^T a(t)dt, \quad v(t) \geq 3km/h, \quad a(t) \geq -0.15m/s^2$
5	Percentage time of Idling (P_i)	-	$Pi, \quad v(t) < 3km/h$
6	Percentage time of Cruising (P_c)	-	$Pc, \quad v(t) \geq 3km/h, \quad -0.15 \leq a(t) < 0.3m/s^2$
7	Percentage time of acceleration (P_a)	-	$Pa, \quad v(t) \geq 3km/h, \quad a(t) \geq 0.3m/s^2$
8	Percentage time of deceleration (P_d)	-	$Pd, \quad v(t) \geq 3km/h, \quad a(t) < -0.15m/s^2$
9	Root mean square (RMS)	m/s²	$RMS = \sqrt{(1/T)\int_0^T [a(t)]^2 dt}, \quad v(t) \geq 3km/h, a(t) \geq 0.3m/s^2$

Table 1: Equations used for calculation of assessment parameters

Results

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. A low number of microtips in streets data is attributed to the absence of traffic signals in streets. Combined with all road types, about 15000 speed-time data were collected. Speed acceleration frequency distribution plot (SAFD), which helps in visualizing driving patterns, is shown in Figure 3 and the normal distribution of speed acceleration is given in Table S2 (SI). The resolution of the SAFD was 5km/hr and 1m/s^2. Speed of the passenger cars varied from 0 to 85 km/hr whereas acceleration ranged from -6 to 4 m/s^2. As figure 3 shows, the speed occurrences were uniformly spread over the total speed range with a significant fraction of idling (when both, speed and acceleration were insignificant) as there were 8 traffic signals exist on the selected route. The peak between 60 to 85 km/hr typically shows the higher speed recorded over the highway whereas the other peak (30 to 60 km/hr) showed speed variation recorded mainly on arteries with some overlapping of highways. The acceleration/ deceleration was more frequent on arteries than highways as arteries were linked with streets, reducing the probability of cruising conditions. Table 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. Figure 4 shows the developed ICDC having large variations of speed over time. The total length of the cycle is 1307s with the first 125 seconds representing the driving pattern in streets, having lower velocities. Overall, the cycle showed multiple idling occurrences depicting the presence of signalized intersections. Deceleration and accelerations are visible before and after each intersection. The maximum speed of ICDC is 76.5km/hr with an average speed of 38.1km/hr. Table 3 compares ICDC with other international driving cycles. Although the 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 the total percentage of cruising mode was high as compared to other driving cycles. Considering the data shown in Table 3, it can be concluded that none of the international developed cycles can be precisely used for passenger car driving patterns in Islamabad and so far, there is not any locally developed driving cycle exist as well.
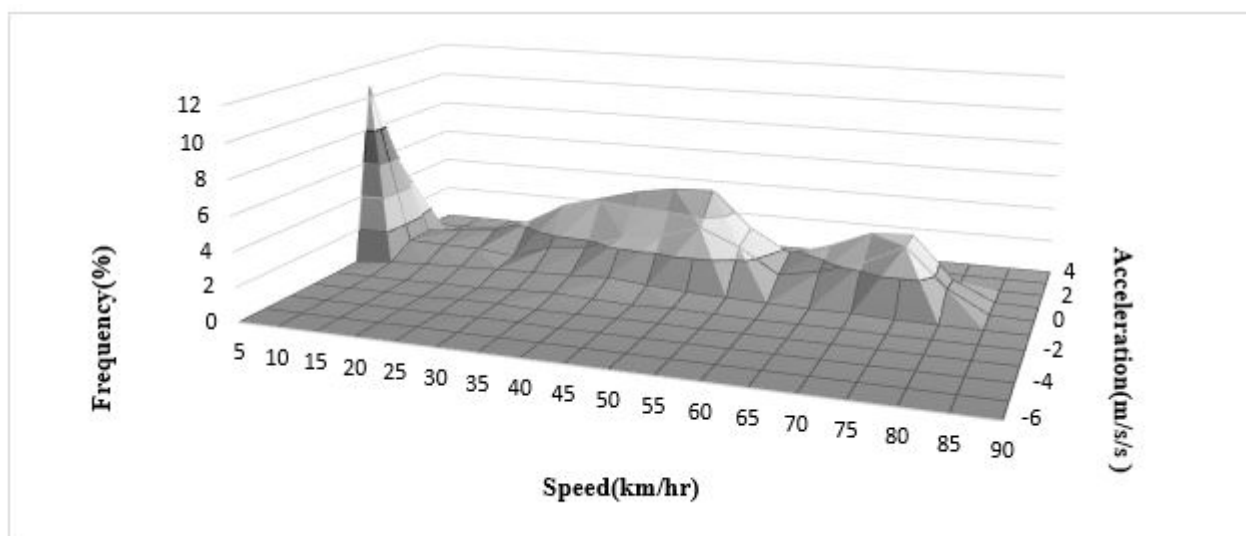

Figure 3: Speed-acceleration frequency distribution for all three types of roads

	V_a	V_r	a	d	P_i (%)	P_c (%)	P_a (%)	P_d (%)	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	24.30	24.33	0.28	-0.33	7.87	26.23	36.37	29.53	0.68

Table 2: Target parameters for three road types of Islamabad

	V_a	V_r	a	d	P_i (%)	P_c (%)	P_a (%)	P_d (%)	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

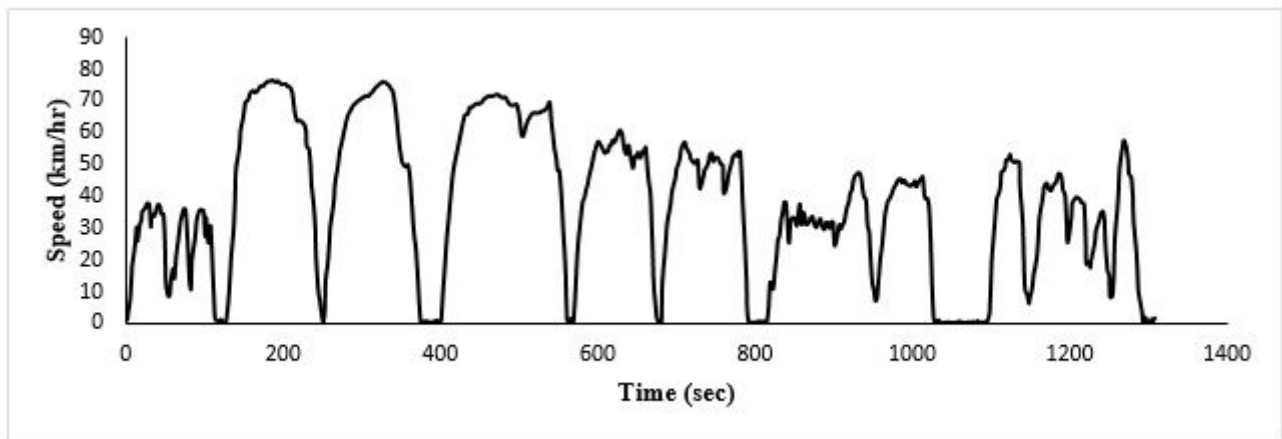**Table 3:** Comparison of target parameters of ICDC with international driving cycles

Figure 4: Islamabad City Driving Cycle (ICDC)

Emission estimation and fuel Consumption of Passenger Car

The engine size and characteristics, fuel injection system, and emission control technology-related data of Islamabad passenger cars were collected in the survey, and cars were categorized into four different types accordingly. Emission and fuel consumption were calculated for selected car types by using CMEM as this is recently used in different emission estimation studies. Besides ICDC, the model was also run for NEDC for comparison purposes. Pollutants were estimated for both cycles and four vehicle types and are presented in Table 4. Estimates for fuel consumption and CO_2 emissions were observed to be 7.9% and 8.8% higher in the case of NEDC than ICDC respectively. Whereas values for CO (39%), HC (16.2%), and NO_x (42.6%) were observed to be lesser for NEDC.

Vehicle Type	ICDC					NEDC				
	Fuel (g/km)	CO_2 (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)	Fuel (g/km)	CO_2 (g/km)	CO (g/km)	HC (g/km)	NO_x (g/km)
Passenger Car 1	63.7	199.3	1.7	0.056	0.347	70.5	220.3	2	0.09	0.181
Passenger Car 2	64.2	200.1	2	0.063	0.319	76.3	238.5	2.1	0.103	0.147
Passenger Car 3	64.8	201	2.6	0.106	0.351	69.5	218.8	1	0.046	0.214
Passenger Car 4	70	217.2	2.9	0.12	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**

Table 4: Comparison fuel consumption and emission estimations of ICDC with NEDC

Conclusion

This study presents the development of the Islamabad City Driving Cycle (ICDC) for passenger cars by collecting speed-time data. This developed driving cycle has its own significance as it can be used to estimate emissions from having the real city data. This Developed driving cycle can also be used for the emissions projections and mitigation or reduction policies can be made according to those results. ICDC was observed to be different from American and European standard driving cycles like NEDC, FTP-72, and ARTEMIS. The developed cycle was further used as input to the CMEM model for estimation of exhaust emissions and fuel consumption by passenger cars in Islamabad city. Four different passenger car types were identified in the vehicular fleet of the city. Four atmospheric pollutants CO_2, CO, NO_x, HC emitted (g/km) and fuel consumed (g/km) were estimated for the passenger cars using ICDC and NEDC as activity inputs to CMEM. Fuel consumption and CO_2 emissions were estimated to be higher for NEDC than ICDC which is attributed to higher idling and higher acceleration and deceleration of NEDC as compared to ICDC. However, estimates for CO, HC, and NO_x were found to be lesser for NEDC.

Acknowledgments

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