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Real world vehicle emissions: Their correlation with driving parameters

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ABSTRACT

Vehicular population in developing countries is expected to proliferate in the coming decade, centred on Tier II and Tier III cities rather than large metropolis. WLTP is being introduced as a global instrument for emission regulation to reduce gap between standard test procedures and actual road conditions. This work aims at quantifying and discernment of the gap between WLTC and real-world conditions in an urban city in a developing country on the basis of driving cycle parameters and simulated emissions for gasoline fuelled light passenger cars. Real world driving patterns were recorded on different routes and varying traffic conditions using car-chasing technique integrated with GPS monitoring and speed sensors. Real-world driving patterns and ambient conditions were used to simulate emissions using International Vehicle Emissions model for average rate (g/km) and Comprehensive Modal Emissions Model for instantaneous emission (g/s) analysis. Cycle parameters were mathematically calculated to compare WLTC and road trips. The analyses revealed a large gap between WLTC and road conditions. CO emissions were predicted to be 155% higher than WLTC and HC and NOx emissions were estimated to be 63% and 64% higher respectively. These gaps were correlated to different driving cycle parameters. It was observed that road driving occurs at lower average speeds with higher frequency and magnitudes of accelerations. The positive kinetic energy required by road cycles, was 100% higher than WLTC and the Relative Positive Acceleration (RPA) demanded by road cycles, was found to be 60% higher in real-world driving patterns and thereby contribute to higher emissions.

Background and historical perspective

The share of the world's population living in cities will grow to nearly 70% by 2050 and energy consumption for transport needs in cities is expected to be much higher, which has already doubled in last 30 years (Dulac, 2012). The light duty vehicles will continue to drive the growth and currently consuming around 20% of the total oil consumed in transport sector (Dulac, 2012). The high fuel consumption and emissions affect the air quality and consequently the human health and environment. Poor ambient air quality (outdoor air pollution) in both cities and rural areas was estimated to cause 3.7 million premature deaths worldwide in 2012. People living in low- and middle-income countries disproportionately experience the

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burden of outdoor air pollution with 88% (of the 3.7 million premature deaths) occurring in low- and middle-income countries, including India, and the greatest burden in the world health organization (WHO) Western Pacific and South-East Asia regions (WHO, 2014).

Vehicle emission standards are the primary technical policy tools available for mitigating emissions from vehicles. The emission test procedures for the light duty vehicles are based on a transient cycle representing driving pattern of a particular country. The light duty vehicle cycles FTP-75 and NEDC are used in US emission and European test procedures, respectively. The China and India are following the NEDC for light duty vehicle emission measurements. The real world driving pattern is a highly dynamic process and it was found during early 1990s that the FTP-75 test cycle does not cover even more than 15% of driving conditions and behaviour encountered in real life operation such as aggressive driving and driving immediately after cold start. So, the development of a real-world driving cycle is important for traffic and transport management, on road vehicular fuel consumption and emission reductions (Andre, 1996; Bata et al., 1994). Various countries have developed driving cycles to analyse different aspects and impacts of local driving conditions, as summarised in Table 1.

These studies bring out the significant difference between certification cycle and real world driving cycle in terms of key driving parameters. The driving cycle is the main parameter for emission testing of light duty vehicles and the deviation from the certification cycle may be the pre-dominant cause for gap between real world fuel economy and type approval data.

Some studies have been carried out, specifically, to assess the gap between certification and real world fuel economy and emissions. The 5th Framework Programme of the European Commission under DECADE project, using intensive measurements on engine dynamometers, chassis dynamometers and in real traffic experiments have established that most of the emissions measured in the certification cycle differed dramatically from the real traffic emissions. (Pelkmans and Debal, 2006; Joumard et al., 2000) carried out a study to understand the influence of driving cycles on unit emissions from passenger cars by considering petrol engines and diesel cars and concluded that as compared to representative cycles, the standardised cycles underestimate hot emissions by almost 50% for petrol engine cars and 30% for diesel vehicles. A recent ICCT study (Franco et al., 2014) compared emission of diesel cars on road with Euro VI limits and certification testing. The study concluded that modern diesel passenger cars have low on-road emissions of carbonmonoxide (CO) and total hydrocarbons (THC), but an unsatisfactory real-world emission profile of nitrogen oxides (NOx). The average, on-road emission levels of NOx were estimated at 7 times the certified emission limit for Euro 6 vehicles.

In India, the Indian Driving Cycle (IDC) was developed in 1985 (Kamble et al., 2009).Further important studies were undertaken consequently (Badusha and Ghosh, 1999; Nesamani and Subramanian, 2011; Anand et al., 2005; Kamble et al., 2009; Grieshop and Boland, 2012). These studies mainly focussed on the methodology of data collection of the real world driving and development of the driving cycle for different category of vehicles. However, few of them reported the difference between real world fuel economy and emission as compared to certification data. A study (Nesamani and Subramanian, 2011) carried out in Chennai revealed that Indian driving cycle does not represent real world driving and emissions were estimated almost two times higher in real world as compared to predictions by IDC. A study (Grieshop and Boland, 2012) on auto rickshaws running in Delhi assessed whether the IDC, used for emission factor development in India, accurately represents emissions from on-road driving or not. The result showed that the IDC systematically under-estimates fuel consumption and emissions; Real-world auto-rickshaws consume approximately 15% more fuel and emit around 49% more THC and contribute 16% more to PM2.5. A study on real-world fuel economy (Pathak et al., 2010) on Dehradun–Delhi highway and Delhi–Jaipur highway concluded that the real world fuel economy in two different highways were significantly different from certification values. The data from the study also established that current practice underestimates the emission rates as compared to complex real world driving conditions.

The studies as mentioned above concluded that for most of the categories of vehicles, average emissions during real world conditions are higher than their average emissions on a standard driving cycle. This may be due to the fact that the standard cycle is generally considered, representing mild driving condition while the real-world driving situations are more dynamic and harsh.

Table 1
Research on driving cycles across the world.

Country	Researcher	Aim
China	Wang et al. (2008a, 2008b)	Driving cycle development and comparison with European and US cycles
Canada	Seers et al. (2015)	Development of two driving cycles for utility vehicles
UK, South Korea	Birell et al. (2014)	Analysis of three independent real-world driving studies
South Korea	Han et al. (2012)	Characterization of driving patterns and development of a driving cycle in a military area
UK	Kumar et al. (2011)	Comparison and evaluation of emissions for different driving cycles of motorcycles
China	Tong et al. (2011)	Development of driving cycles for motorcycles and light-duty vehicles in Vietnam
Vietnam	Tung et al. (2011)	Development of emission factors and emission inventories for motorcycles and light duty vehicles in the urban region
China	Peng et al. (2015)	Construction of engine emission test driving cycle of city transit buses
India	Nesamani and Subramanian (2011)	Development of driving cycle for intra city buses

There have been extensive studies on the application of American or European emission models, such as IVE, CMEM, MOBILE and COPERT into non-US regions to assess vehicle emissions. (Höglund and Niittymäki, 1999) have explored and verified the methodology and use of micro simulation to estimate vehicle emissions. Since then, the models used in this work have been extensively used for emission modelling and analyses, as summarised in Table 2.

It should be noted that these emission models are designed specifically for US and European regions. Therefore, differences between developing countries like China, India and these developed countries in vehicle operating condition and emission performance will lead to significant emission estimation biases, as the model is not comprehensively revised due to the closed model structure or the lack of valid data. However, above models are useful in estimating the impact of driving pattern on emissions.

Previous studies have mainly followed two approaches to estimate the difference between the real world emission and standard cycle measurements (as per legislation). The first approach is to collect driving data from the real world using GPS or ECU and compress the data in such a way to from a representative cycle (about 20–30 min) by maintaining a close deviation (<5%) to the pool data acquired in real world driving trips. This approach has a limitation of moderately representing the real world driving condition as based on different considerations, hundreds of hours of driving data is compressed to few minutes and the very high acceleration and sudden braking conditions can't be satisfactorily simulated on chassis dynamometer. The compressed driving cycle represents a compromise of different driving parameters and laboratory limitations and often deviates significantly from real world conditions. The second approach is to use portable emission analyser on-board and collect the real world driving condition and emissions simultaneously. However, in case of light commercial vehicles, because of very heavy on-board equipment, practical life loading is not represented and also poses a restriction on the normal real world driving. Moreover, the testing is time consuming and expensive. So, it is difficult to acquire data of the large number of trips (to represent all the real world driving condition) in a short time and economically.

The methodology used in present work is unique in the sense that it represents the emissions and characteristics of a no-bias study, real world driving pattern. The driving pattern of real world is directly fed into emission models without any alteration (like compression of driving data in driving cycle based approach), which give reasonable estimates of every trip, thus accounting for different aspects such as driver aggression and traffic conditions, without being biased towards certain regions of driving behaviour or restricted by laboratory equipment. The estimated results were normalized based on emission measurement in laboratory and eliminates any systematic bias in the emission model or parameter, and provides a measure of extent of deviation of real world conditions. The other important features of this study are that it was performed for modern vehicles (Euro 4) and presents the deviation of the real world emission as compared to new World Harmonized Light-duty Vehicles Test Cycle (WLTC) along with co-relation of the key driving parameters and emissions. WLTC is a new test driving cycle, defined under the Worldwide harmonized Light vehicles Test Procedures (WLTP) which is a global harmonized standard for determining the levels of pollutants and CO2 emissions, fuel or energy consumption, and electric range from light-duty vehicles (passenger cars and light commercial vans). It is being developed by experts from the European Union, Japan, and India under guidelines of UNECE World Forum for Harmonization of Vehicle Regulations.

In this study, vehicles were driven in city driving conditions fitted with GPS to extract the vehicle operation at various time of the day to acquire all the driving situation of the real world. These driving data (GPS file) has been used as an input to the models like IVE and CMEM to compare the emission factor of certification cycles (MIDC and WLTC) along with local conditions of temperature and humidity. These models are based on critical physical parameter of driving and capable of predicting the impact of driving pattern on emissions. Each individual driving trip was also analysed for key driving param-

Table 2
Usage of emission models across the world.

Emission model	Research by	Application
IVEM	Zhang et al. (2011)	Comparison of free flow traffic emissions
	Wang et al. (2008a, 2008b)	On road vehicle emission inventory for Shanghai, China
	Mishra and Goyal (2014)	Estimation of vehicular emissions using dynamic emission factors: a case study of Delhi, India
CMEM	Nagpure et al. (2011)	Emission estimation of gasoline vehicles in India
	Lents et al. (2004)	Comparison of on-road vehicle profiles collected in seven cities worldwide
	Zhanbo et al. (2015)	Trajectory-based vehicle energy/emissions estimation for signalized arterials using mobile sensing data
	Davis et al. (2005)	Fleet emissions in developing countries
COPERT	Lozhkina and Lozhkin (2015)	Estimation of road transport related air pollution in Saint Petersburg using European and Russian calculation models
	Marmur and Mamane (2003)	Comparison and evaluation of several mobile-source and line-source models in Israel
	Ganguly and Broderick (2008)	Performance evaluation and sensitivity analysis of the general finite line source model for CO concentrations adjacent to motorways
MOVES	Jeong et al. (2015)	Emission evaluation of inter-vehicle safety warning information systems
	Wu et al. (2014)	Sensitive analysis of emission rates in MOVES for developing site-specific emission database

eters and compared with certification cycles. The use of two different models serves two purposes. First, the comparison of trends in emission prediction from the two models serves as verification criteria. Second, IVE provides average emissions in term of grams per kilometre and CMEM provides instantaneous emissions in terms of grams per second. This enables both overall and second-by-second analysis.

In this study, road cycles were compared with MIDC and WLTC standard cycles, respectively, the current and future certification standards. MIDC is the current standard emission test cycle for India, adapted from NEDC by lowering maximum speeds. WLTC is a new cycle which will be implemented in India for the emission testing in future. Thus it becomes critical to analyse this cycle keeping in mind future development of emission regulation. However, due to standardization, a gap is created from the individual characteristics of each country. Moreover, typical driving patterns focus on large urban cities like Mumbai in India. However, Tier-II cities have significantly different driving conditions and are expected to dominate road emissions in India. This work aims at quantifying the gap between WLTC and road conditions in such urban centres in India. This study is an advancement over the previous studies as it comprehensively asses the real world driving pattern and emissions in a Tier II city, on modern vehicles (Euro 4) and compares with futuristic emission cycle (WLTC) using the emission models for both average and modal emission analysis. The correlation of the driving parameter and the emission is also an important feature of this study.

Methodology

The methodology in the flow of the activities of this work is given in Fig. 1.

Test vehicles

The specifications of the test vehicle fleet for driving data acquisition and emission measurement in the laboratory are given in Table 3.

Emission testing of test vehicle in vehicle emission laboratory

In the present study four Euro 4 light duty gasoline vehicles (see technical details in Table 3) were tested over the MIDC using gasoline fuel. The tests were carried out in the Vehicle Emission Laboratory (VELA) at the CSIR – Indian Institute of Petroleum, Dehardun, India. The facility includes a climatic test cell with controlled temperature and relative humidity (RH) to mimic different ambient conditions (temperature range: 20–30 °C; RH range: 35–60%). The tests were performed on a chassis dynamometer (inertia range: 150–6500 kg), designed for two and four-wheelers LDVs (two 48″ rollers). The exhaust was fed, as defined by the regulation (70/220/EEC) and its following amendments (EEC, 1970), to a Constant Volume Sampler (CVS i60, AVL, Austria) using a critical Venturi nozzle to regulate the flow (CVS flow range: 3–30 m^3/min). Gaseous emissions were analyzed from a set of Tedlar bags. The bags were filled with diluted exhaust from the CVS (Automatic Bag Sampler, CGM electronics) and CO, total hydrocarbons (THC), NO_x, and CO_2 concentrations were measured using an integrated measurement system (AMA i60, AVL). A series of thermocouples monitored the temperature of the oil, cooling water, exhaust, and ambient conditions. Vehicles were kept inside the climatic cell under the described conditions for a 24 h soaking period prior to each emission test. The test cell configuration is shown in Fig. 2.

Base emission adjustment factor

The average values along with standard deviation are shown in Fig. 3.

It can be seen in Fig. 3 that emission values for all the vehicles are lower than the type approval limits for Euro 4 light duty gasoline vehicles. Based on the above, the base emission adjustment factors were determined and applied for the emission estimation by IVE model for real world driving trips.

Road cycle acquisition

Light gasoline passenger cars with kerb weights in the range of 1000–1200 kg were used to collect on-road driving data. The car-chasing technique was used to acquire the driving patterns of cars. Professional drivers were employed to drive cars to follow the traffic in defined routes and specially-designed instruments were used in the cars to store the vehicle speed second-by-second. A set of parallel equipment – a Global Positioning System (GPS) receiver and a speed sensor was used for data quality control purpose. Three representative routes specifically representing congested, medium and lean traffic conditions in a typical Indian city were selected for the data collection as shown in Fig. 4.

To represent daily road activity, trips were conducted covering the entire active traffic hours of the city, as shown in Fig. 5. The time of test trips were classified as rush hours and off-peak. The numbers of trips were carried out as almost twice in peak hours as compared to off peak hours.

To nullify variability due to driver behaviour, the different drivers were rated by test running of the vehicle on a specific route and traffic conditions, along with measurements of fuel consumption, speed and braking data. The driver evaluation

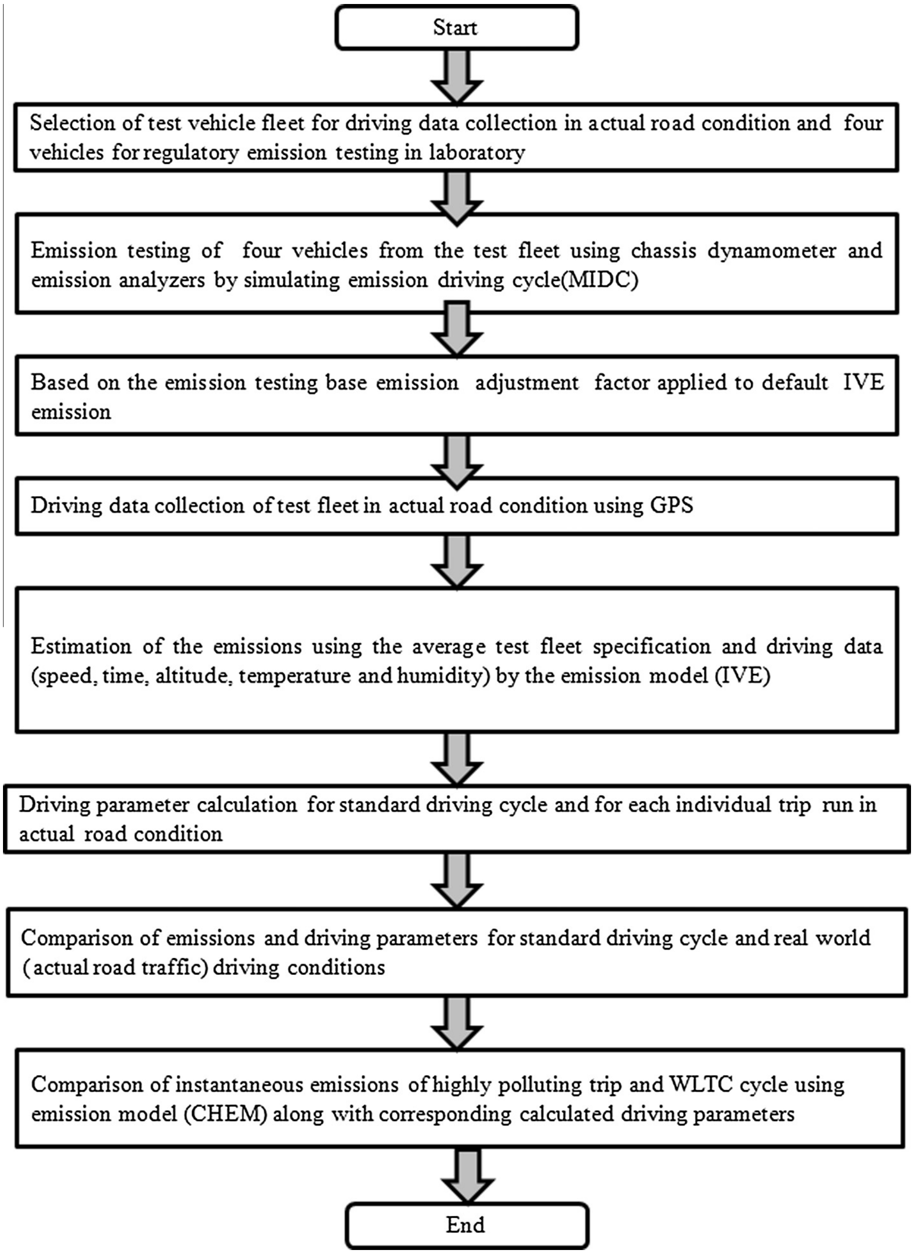

Fig. 1. Methodology of the present work.

Table 3
Specification of test vehicles.

Vehicle fleet	Type 1	Type 2	Type 3	Type 4
Fuel	Gasoline	Gasoline	Gasoline	Gasoline
Emission type	Euro IV	Euro IV	Euro IV	Euro IV
Engine capacity, cc	998	998	1086	1197
Compression ratio	10.0:1	9.1:1	8.9:1	11.1:1
Maximum power	68 PS @ 6000 rpm	68 PS @ 6000 rpm	62 bhp @ 5500 rpm	84.3 PS @6000 rpm
Maximum torque	90 Nm @ 3500 rpm	90 Nm @ 3500 rpm	96 Nm @ 3000 rpm	115 Nm@4000 rpm
Kerb weight, kg	750	870	854	965
Gross vehicle weight, kg	1210	1350	1250	1415
Catalyst	TWC	TWC	TWC	TWC

Fig. 2. Test cell configuration.

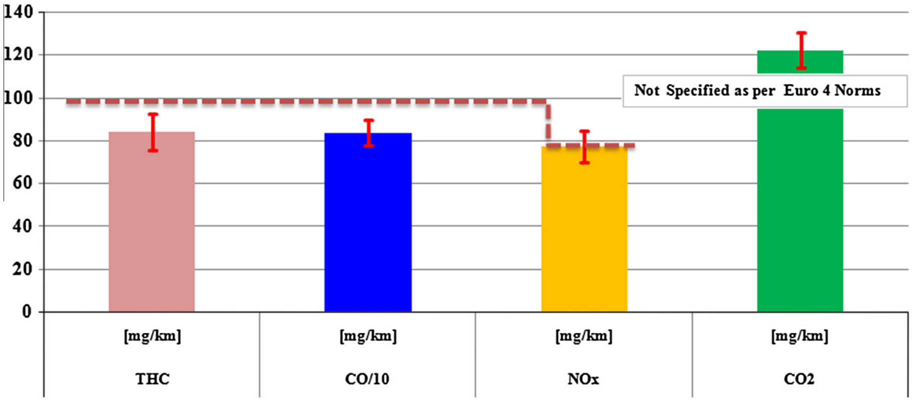

Fig. 3. Base emission adjustment factors.

runs were repeated several times. The logged data for each driver was processed using the software and drivers were given rating as Excellent (E), Good (G) and Poor (P), considering parameters defined in Table 4.

In this study, twelve drivers were employed, equally representing each driver rating for recording road driving patterns. The test runs were well mixed with the driving routes and the quality of drivers to minimize the impact of the driver behaviour on the acquisition of real world driving pattern.

Simulation methodology

Macroscopic models are usually used for large-scale analysis, such as estimating comprehensive emission factors (Appendix Table A1) or total emission amount of an area. IVE, MOBILE and COPERT are the most generally used models. Microscopic emission models like CMEM are capable of evaluating traffic impact on environment in project level. Microscopic models (Zhang et al., 2011) were used to estimate emission for road and standard driving cycle, since these models can suitably estimate vehicle emissions in congestion and other driving conditions. Models such as the Comprehensive Modal Emissions Model (CMEM) and the International Vehicle Emissions (IVE) model can estimate emissions for temporal scales ranging from second to hours, and for specific vehicles as well as vehicle fleets. These models explicitly account for idling, accelerating, cruising and decelerating engine operating conditions, and can simulate second-by-second speed and power fluctuations of vehicles on a road network. IVE and CMEM models have been extensively used to estimate vehicular emissions for road cycles (Höglund and Niittymäki, 1999; Zhang et al., 2011; Edward et al., 2002; Nagpure et al., 2011; Hui et al., 2007).

The IVE model is a computational tool which is designed to estimate emissions of local air pollutants, greenhouse gases, and toxic pollutants from motor vehicles. Unlike other models (e.g. MOBILE, EMFAC, COPERT, CMEM, MOVES) IVE model takes into account the different technologies and conditions that exist in developing countries like India. The model uses

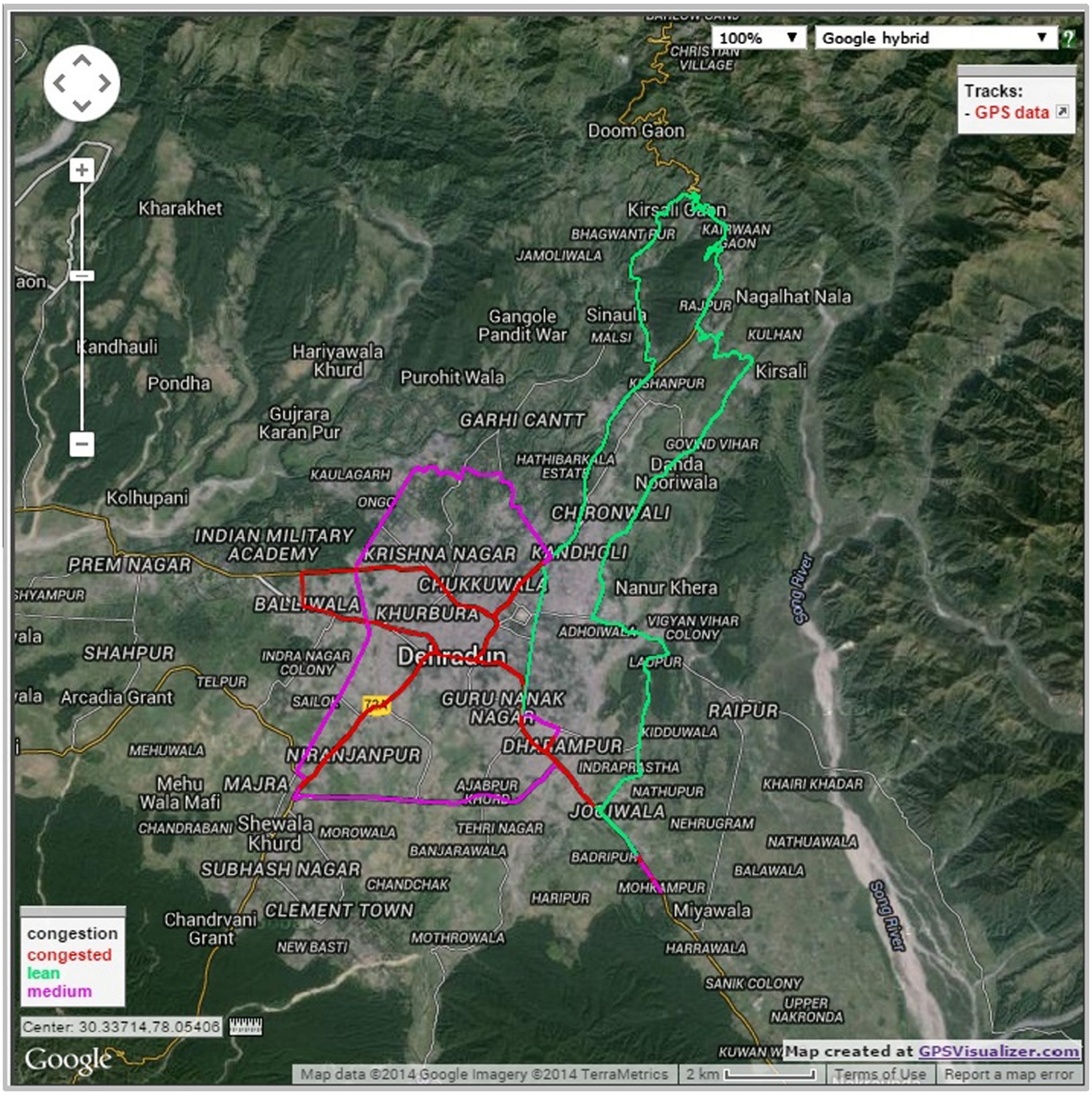

Fig. 4. Experimental routes for collection of road cycles in different traffic conditions.

emission factors based on detailed vehicle technology classification to simulate a diverse vehicle fleet in detail. The basic emission calculation process in IVE model applies a base emission rate with a series of correction factors to estimate the amount of emissions from a variety of vehicle types in local level. It generates average emission levels of different emissions (Nagpure et al., 2011; IVE Model User's Manual, 2008).

The Comprehensive Modal Emissions Model (CMEM) is a physically-based, power demand model. It predicts fuel consumption and emissions of CO, HC, NOx and CO_2 for different modes of vehicle operation, e.g., idle, cruise, acceleration and deceleration. The entire emissions process is broken down into different components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is then modelled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, and emission technology (Scora and Barth, 2006).

In this study, both CMEM and IVE models are used to estimate emissions. Speed-time-altitude data recorded from road driving were directly used as input to the models along with required suitable parameters for each model, defined in Table 5. Although there was a slight difference in absolute values, the trends and proportions of emission estimations were similar.

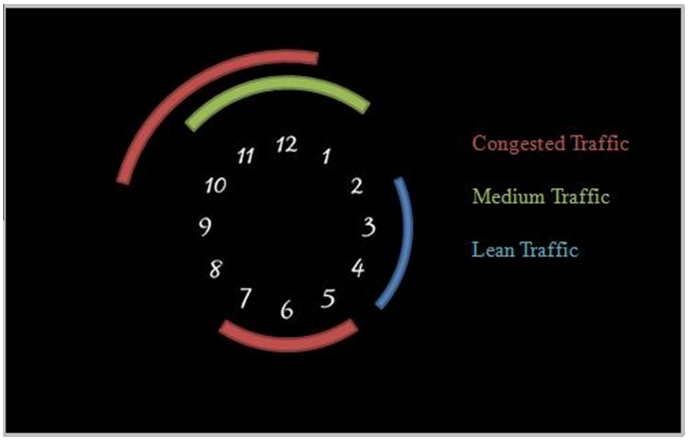

Fig. 5. Time of collection of driving data over different periods in the day with varying traffic congestion.

Table 4
Parameters for the rating of the drivers.

Parameters	Good driving practise	Poor driving practise
Maximum speed	Moderate	High
Acceleration (average and maximum)	Low and steady	High and sharp
Braking frequency	Minimum	High
Cruising duration	Maximum	Low
Idling	Minimum	Moderate
Deceleration	Low and steady	High and sharp
Anticipation level	High	Low

Table 5
Emission model inputs.

IVE model inputs	
Fleet	117: Petrol-auto/small truck-light-MPFI-PCV: <79 K km (100%)
Altitude	800 m
I/M class	None
A/C usage	0.0%
Fuel characteristics	Moderate/premixed gasoline – sulfur (300 ppm) – lead (none) – benzene (0.5%)
Soak time	6 h (100%)
VSP bins	Cycle defined
Temperature, humidity	Cycle defined
Distance, average speed	Cycle defined
CMEM model inputs	
LD vehicle	Category 6 car, normal emitting, TWC, fuel-injected, <50 K miles, low power/weight
Vehicle mass	1200 kg
Specific humidity	Cycle defined
Fleet	Single model vehicle (100%)

Cycle parameters calculation

To compare driving cycles, many parameters can be considered. SAFD (Speed–Acceleration-Frequency-Distribution) or SAPD is used to represent typical operation characteristic of a driving cycle (Nesamani and Subramanian, 2011; Hung et al., 2007; Sileghem et al., 2014). Modal analysis of a cycle into acceleration, deceleration, idle and cruise is also a popular methodology producing important results (Kamble et al., 2009; Frey and Unal, 2002; Tsai et al., 2005; Unal et al., 2004). Recent studies in India (Bokare and Maurya, 2013) have also shown usefulness of this approach. Sileghem et al. (2014) have used RPA and average speed as benchmark for comparing WLTC with NEDC and CADC cycles and their corresponding emissions. Unal et al. (2004) have also considered standard deviation of speed to explain emission trends. Hung et al. (2007) have considered parameters like average acceleration, deceleration, PKE and RMS acceleration in their development of practical driving cycle.

Weijer (1997) reviewed the correlation of various cycle parameters to emissions and found RPA, Average Speed, Positive Kinetic Energy, Standard Deviation of Speed, Average Positive Acceleration and RMS Acceleration as most important parameters. Berry (2010) used same parameters to compare real world driving cycles with standard cycles employed in the US. Smit et al. (2006) also used these parameters to develop VERSIT + emission model. Barlow et al. (2009) in the Reference book of driving cycles have calculated these parameters for standard cycles used globally in consideration of their usage. Most relevant parameters for road and standard cycles were calculated to compare and contrast driving patterns.

Results and discussion

WLTC and MIDC comparison

MIDC is currently being employed in India as the standard for emission certification, and is derived from NEDC with lower maximum speeds, while India is contributing to the development of Worldwide Harmonized Light Vehicles Test Procedure, which is expected to represent road driving conditions. However, due to input from different geographies, the gap from each particular area increases. Table 6 compares different cycle parameters and average emissions for WLTC and MIDC. The graphical representation of the MIDC and WLTC cycle is shown in Fig. 6 MIDC is a combination of the driving modes presented in the form of the smooth straight lines and the WLTC is bit more transient in nature to simulate real world driving pattern in a better way.

In term of parameters, MIDC and WLTC both have similar average speeds. However, MIDC seems to have higher average acceleration as compared to WLTC. But PKE, which most closely correlates emissions in vehicles, is higher in WLTC as compared to MIDC. The stress on the engine, represented by RPA, is extremely low in MIDC as compared to WLTC. As observed, emissions from MIDC are only slightly lower than WLTC.

SAFD (Speed–Acceleration Frequency Distribution)

The typical real world driving trips and standard cycles (MIDC and WLTC) are shown in Fig. 6. It can be observed from Fig. 6. That the speed and time pattern is significantly different (complex) from standard driving cycles (smooth).

SAFD demonstrates the distribution of the driving pattern observed in each speed and acceleration class. Fig. 7 shows MIDC and WLTC as compared to the typical zone in which road driving operate.

Standard cycles are designed to operate in specific v–a region. This allows 'cycle-beating' techniques by manufacturers (Kamble et al., 2009).The maximum speeds of MIDC (90 km/h) and WLTC (85 km/h) are much higher than typical speeds acquired on urban roads. Though operating at higher speeds, the cycles have smoother transitions and fail to catch the acceleration ranges of a real vehicle. Both standard cycles operate within a range of $\pm 1.5\ \mathrm{m/s^2}$ which is much lower than the operating range of real world driving patterns ($\pm 2.5\ \mathrm{m/s^2}$ for most cases) with a significant dispersion even beyond those limits.

Road cycles operate at much lower speeds because of traffic conditions in India but have much higher acceleration rates. These lower speeds also subsequently mean that vehicles operate at lower gear ratios with higher engine speeds. Higher dispersion in negative values also indicates intensive braking by the vehicles, whereas in standard cycles, acceleration and deceleration are almost equal.

Positive Kinetic Energy (PKE)

PKE is the acceleration energy required in a certain driving pattern (see Appendix A). PKE is an indicator of how much energy the engine produces to follow a certain driving pattern, and is among the best indicators for engine emission predictions. Fig. 8 represents the distribution of deviation of PKE of road cycles as compared to WLTC.

The simulated results estimate PKE of WLTC to be approximately $0.257\ \mathrm{m/s^2}$ with the road cycle falling in a range of up to $0.76\ \mathrm{m/s^2}$, the median lying nearly around $0.44\ \mathrm{m/s^2}$. PKE of road Cycles have mean deviation approximately 100% higher

Table 6
Comparison of WLTC and MIDC.

Parameter	WLTC	MIDC
Average speed	35.72	32.55
Average positive acceleration	0.28	0.49
Average negative acceleration	−0.32	−0.58
RMS acceleration	0.129	0.186
Positive kinetic energy	0.257	0.184
Relative positive acceleration	0.125	0.087
Acceleration percentage time	33%	16%
Deceleration percentage time	27%	14%
Cruise percentage time	21%	43%
Idle percentage time	18%	27%
Average CO emissions	0.774	0.679
Average HC emissions	0.039	0.041
Average NOx emissions	0.223	0.201
Average benzene emissions	0.00060	0.00191

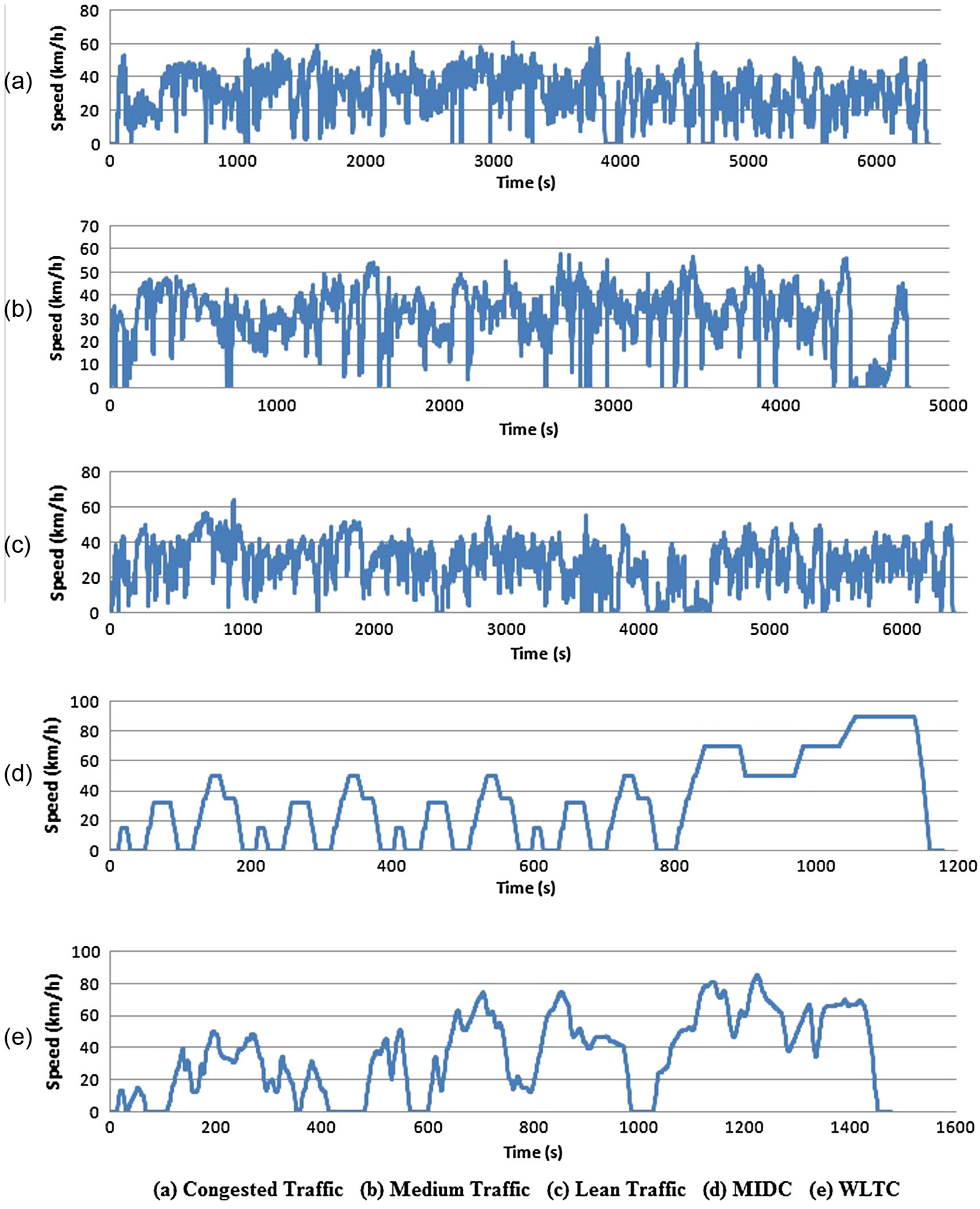

Fig. 6. Speed time pattern of real world trips and standard driving cycles. (a) Congested Traffic. (b) Medium Traffic. (c) Lean Traffic. (d) MIDC. (e) WLTC.

than WLTC and a standard deviation of 36%. The interquartile range of PKE deviation is 76–125%, implying that in terms of PKE, there is a systematic gap from the standard cycle, whereas the road cycles have moderately dispersed deviation. This implies that road cycles have significantly higher energy demand per kilometre as compared to standard cycles. This higher demand created higher temperatures and fuel consumption, leading to higher emissions.

Relative Positive Acceleration (RPA)

The RPA of a typical WLTC cycle is estimated to be approximately 0.124 m/s^2, with road cycles distributed around 0.15 m/s^2–0.18 m/s^2 ranges primarily.RPA is the positive power input required in a certain driving pattern averaged over the distance of the cycle (see Appendix A). The RPA is a value that characterises the load of the trip and it is often used as a factor

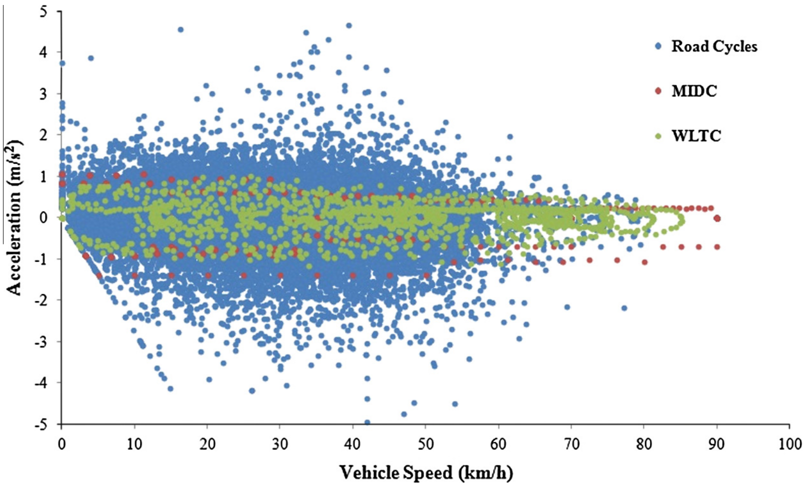

Fig. 7. Acceleration vs. speed for road cycles, MIDC, WLTC.

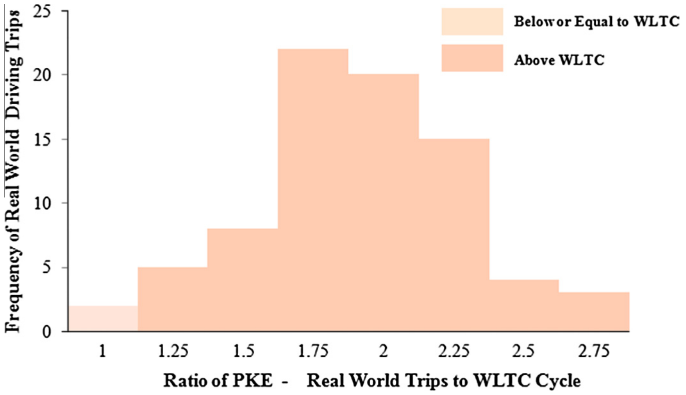

Fig. 8. Histogram of PKE for on-road to WLTC cycle ratio.

to compare different test cycles (Sileghem et al., 2014; Weijer, 1997). The comparison of RPA of road cycles as compared to WLTC is demonstrated in Fig. 9.

The road cycles have a mean deviation of approximately 60% higher than WLTC standard with a standard deviation of 29%. RPA is spread in an interquartile range of 45–78% deviation from WLTC. Thus, a practical urban drive creates much

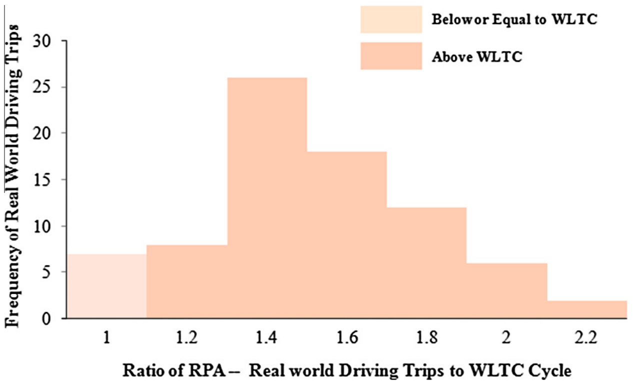

Fig. 9. Histogram of RPA for on-road to WLTC cycle ratio.

higher loads on the vehicle as compared to standard cycles used in certification testing. This indicates a large gap in terms of relevance of these cycles in representing real world conditions.

Average speed

Higher average speeds have positive correlation with higher emission levels; however, the driving load depends on speed as well as acceleration rates. Constant high speeds might lead to lower emissions than lower speeds with more accelerations and decelerations. Fig. 10 shows the deviation of real world urban average speeds from WLTC standard.

Indian road cycles have 23% lower average speeds as compared to WLTC with a standard deviation of 13%. Most other standard cycles also have significantly higher average speeds. Majority of road cycles, understood from the interquartile range of 12–33% operate in a narrow band of speeds. More specifically, WLTC averages at speed of approximately 35 km/h whereas road cycles lie largely in the range of 23–31 km/h. This can be understood from the fact that overall traffic speed of the city is almost similar. The frequent stops and congestion in Indian cities lead to much lower average speeds.

Standard Deviation of Speed indicates how much the instantaneous speed of the cycle varies from the overall cycle average. Higher standard deviations in speed indicate either higher accelerations or accelerations may be lower in magnitude but sustained over a period of time. The standard deviation of speed of road cycles has a mean 37% lower than WLTC with a standard deviation of 8.5%. This implies road cycles operate in a relatively narrow range of speeds, as was also apparent from SAFD and have lower variations in terms of speed. However, this does not describe the frequency of variation in speed, simply the magnitudes. Standard cycles have sustained periods of different speeds, which is in contrast with road cycles where frequent fluctuation in a narrow range of speed is observed.

Average Positive Acceleration

Average Positive Acceleration indicates the degree of overall positive acceleration in a driving pattern. Higher acceleration implies higher energy demands, thus higher emissions and fuel consumption. Fig. 11 compares average positive acceleration of road drives with WLTC.

The average positive acceleration of WLTC is calculated to roughly 1 m/s^2.The average positive acceleration of road cycles have a mean 55% higher than WLTC with a standard deviation of 25%, implying that road cycles operate on wide range of average acceleration higher than WLTC. Though acceleration-based measures have much higher variance than speed-based measures for road cycles, the inter quartile range of average positive acceleration lies between 40% and 70% deviation from WLTC. Road cycles demonstrate a large variation from standard cycles in terms of acceleration, pointing to a large gap between real world and standard cycles.

RMS Acceleration is a measure how frequently and how much acceleration varies over the driving cycle (see Appendix A). A high RMS Acceleration indicated rapid acceleration and breaking. This leads to higher engine stresses and thus higher emissions.

RMS Acceleration of road cycles has a mean 500% higher than WLTC with a 240% standard deviation. WLTC has an estimated RMS Acceleration of approximately 0.13 m/s^2 while the RMS acceleration is widely distributed in a range of up to 1.7 m/s^2. This implies that in real world, very frequent acceleration and breaking occur, keeping speed in a narrow range, with high accelerations, thus having significantly higher power demand and therefore more emissions as compared to standard cycles.

The interquartile range of RMS acceleration also lies between 230% and 545% deviation. This indicates a very large range of acceleration tendency and indicates effect of different driving styles. However, the central tendency of the percentage variation points to a large gap between road and standard cycles.

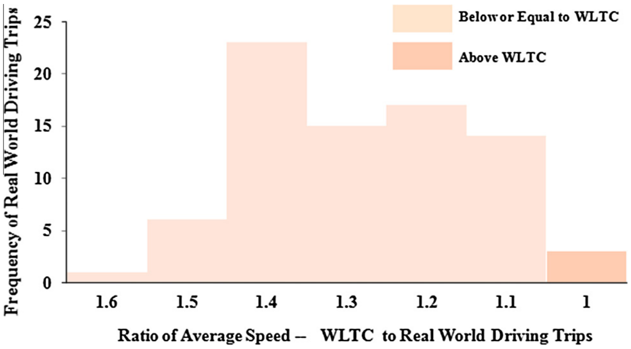

Fig. 10. Histogram of average speed for WLTC to on-road ratio.

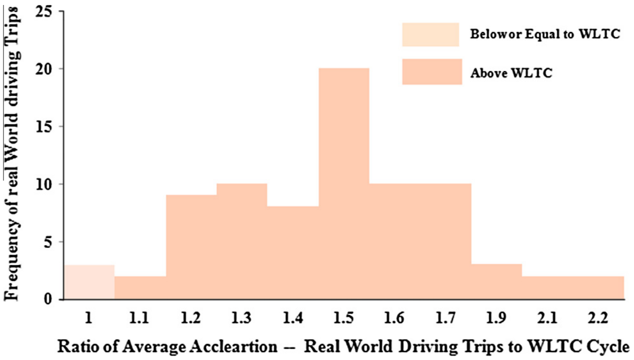

Fig. 11. Histogram of average positive acceleration for WLTC to on-road.

Emissions

As discussed, real world driving cycles show a significant departure from standard cycles in terms of cycle parameters. However, the basic purpose of a standard driving cycle is to estimate emissions. Fig. 12 shows CO emissions of road cycles simulated on IVE model as percentage deviation from WLTC simulated results using the same model and parameters.

For the given vehicle specifications, the simulated CO emissions in a typical WLTC cycle are estimated to be 0.953 g/km. Although most road cycles are concentrated roughly around 1.4 g/km, large deviations are observed in extreme cases.CO emission of road cycles is a mean 155% higher than WLTC emissions. CO emissions show highest deviations from standard cycle values. CO also shows the largest variation in absolute emission levels, with a standard deviation of 120% and an interquartile range of 63–220% deviation from WLTC. Thus, it becomes very difficult to bracket the CO level deviation; nevertheless, it is apparent that CO emissions show a major gap in road and standard cycles.

It is shown in Fig. 13 that HC emissions are in general higher by 63% than WLTC simulated levels. HC emissions also show large variation in simulated levels, the simulated levels for WLTC being roughly 0.080 g/km with a standard deviation of 28% and the interquartile range lying between 45% and 80%. Thus, even neglecting very high emission predictions, standard cycles still underestimate emissions in the real world.

Fig. 14 demonstrates NOx as percentage deviation from WLTC simulated on IVE model.

WLTC emissions for NOx are simulated to be roughly 0.086 g/km. NOx emissions show trends very similar to HC emissions, with a mean of 64% deviation from WLTC and an interquartile range lying between 38% and 82%. The standard deviation of 31% shows that despite some extreme values, NOx shows a systematically higher trend in real world driving pattern as compared to standard WLTC cycle.

Apart from regulated emissions, CO_2 emissions are important consideration because of increasing concerns for greenhouse gas emissions. Fig. 15 shows CO_2 emissions as percentage of WLTC as simulated on IVE.

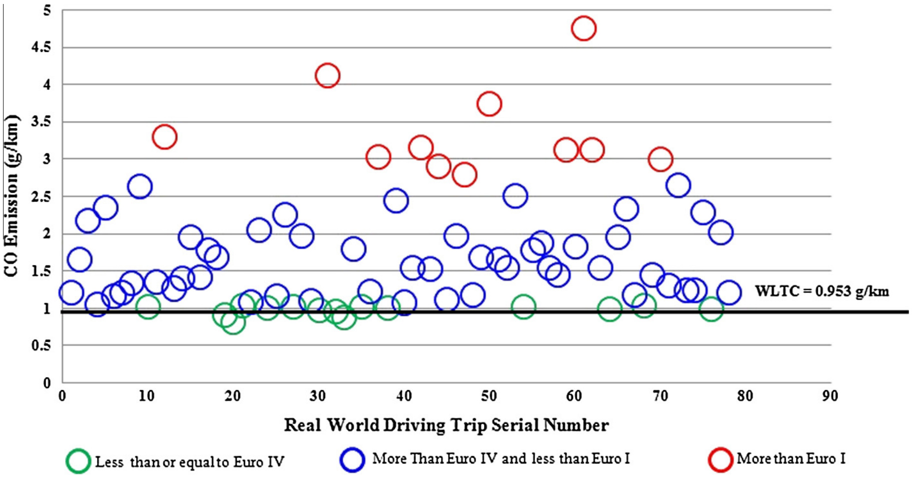

Fig. 12. On-road CO emission (g/km).

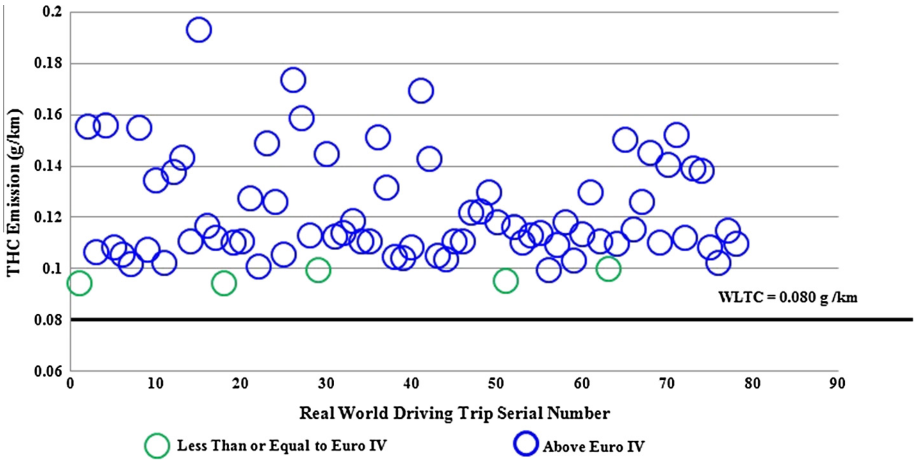

Fig. 13. On-road HC emissions (g/km).

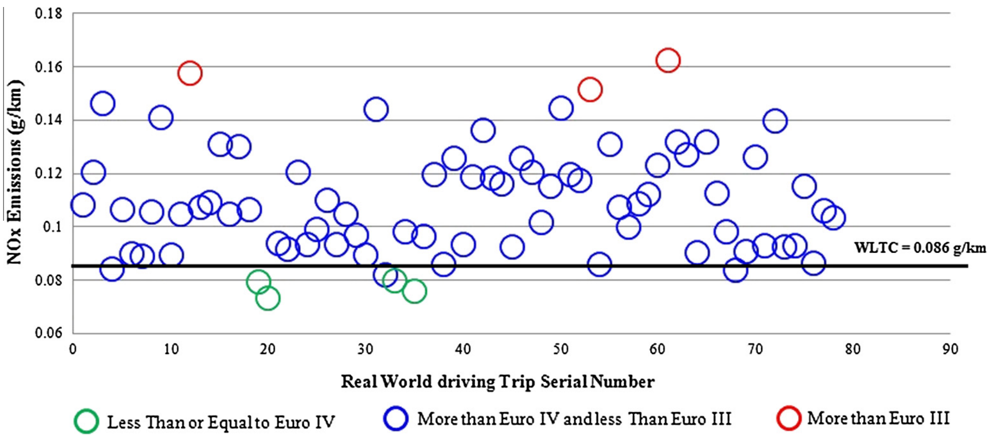

Fig. 14. On-road NOx emissions (g/km).

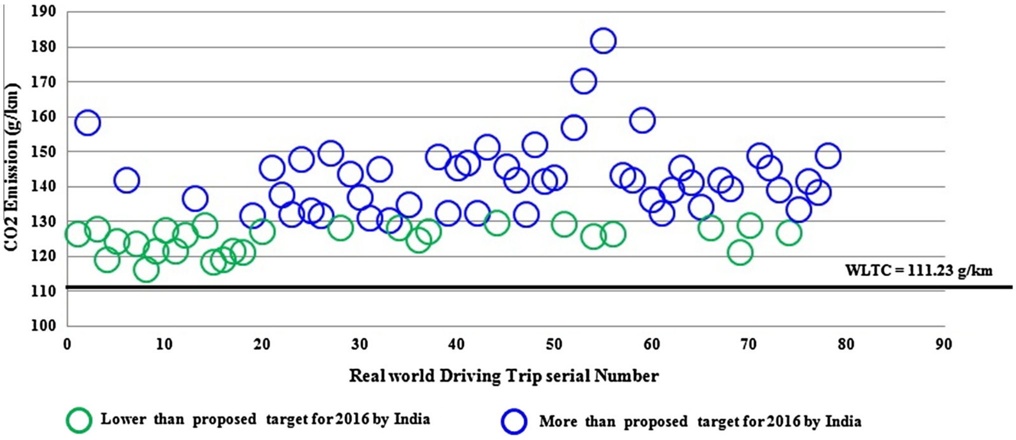

Fig. 15. On-road CO_2 emissions (g/km).

CO_2emissions also point to the gap between real world and standard emission estimations. Road cycles show a mean 31% higher than WLTC CO_2 levels. CO_2 levels for WLTC being simulated to 111.23 g/km for WLTC with a standard deviation of 12% and an interquartile range of 23–38%, CO_2emissions occur in a relatively narrow range, consistently higher than WLTC.

In addition to above, Benzene is a highly carcinogenic emission. Monitoring of benzene is gaining acceptance and importance worldwide. The benzene emissions for WLTC were simulated around 0.017 g/km. Benzene emissions from road cycles are on average 42.26% higher than WLTC with a mean deviation of 40.4%. The emissions lie in an interquartile range of 34.5–61.04%, representing a comparatively narrow range with high magnitudes. The significantly high benzene emissions from road cycle represent a highly alarming trend in toxic emissions.

Correlation

Deviation of cycle parameters can be used to explain the higher emission predictions as discussed earlier. Weijer (1997) established the correlation of various cycle parameters and emission levels. PKE, representing energy input for a driving pattern can be used to explain the gap between emission predicted for standard and road cycles. Fig. 16 shows the CO emissions simulated on CMEM as bubble size correlating PKE and average speed for representative high, medium and low emission road cycles in comparison with WLTC and MIDC.

Fig. 16 shows that even though road cycles have comparable average speeds with the most polluting road conditions, the energy requirements, represented by PKE is significantly lower than road cycles. This leads to much lower CO emissions, which strongly correlate with PKE.

The PKE of representative cycles chosen range from 1.2 times WLTC for the low emissions to 2.2 times for the high emission road cycles. The average speeds of high emission cycles are roughly equal to WLTC, whereas the low emission road cycles have speeds 60–70% of WLTC. The high emission cycles have CO prediction roughly 8 times than WLTC, whereas the low emissions range from 1.2 to 1.5 times the WLTC levels, medium being 5–6 times the WLTC levels.

HC emissions also correlate to PKE Weijer (1997). Fig. 17 shows the HC emissions simulated on CMEM as bubble size correlating PKE and average speed for representative high, medium and low emission road cycles in comparison with WLTC and MIDC.

HC emission correlations show similar trends to CO emissions. The same representative high, medium and low emission cycles are used as in CO emissions. HC emissions in high emission cycles are roughly 3 times the emission predicted for WLTC. The low emission cycles are predicted to give 1.2 times the WLTC emissions, the medium cycles averaging 2.2 times the standard cycle value. The higher energy demands in comparatively moderately emitting road cycles produce more than twice the HC emissions as estimated using WLTC.

Different emissions correlate strongly with different cycle parameters. NOx have been shown to correlate strongly with RPA of a driving pattern Weijer (1997), which represents the load exerted during a cycle. Fig. 18 shows the NOx emissions simulated on CMEM as bubble size correlating RPA and average speed for the same representative high and low emission road cycles as used in the HC and CO analyses in comparison with WLTC and MIDC.

The variation within the representative road cycles in terms of NOx emissions is lower as compared to HC and CO emissions, with low emission cycles averaging 1.5 times NOx emissions as compared to WLTC, whereas high emission cycles are predicted to give roughly 2 times the WLTC value.

The RPA of the chosen representative cycles range from roughly 1.1 to 1.5 times the RPA of WLTC. This variation reflects in the NOx emission for the gasoline vehicle simulated under the given conditions.

Driving modes

Driving modes represent the aggregate behaviour of a driving cycle. Rather than analysing second by second data, driving modes represent the natural and logical division of a road cycle into broad segments, in which vehicle behaviour, and correspondingly the emissions vary (Appendix Table A2).

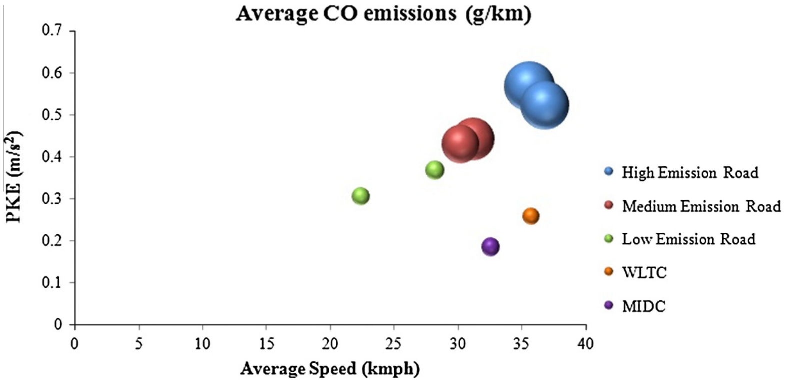

Fig. 16. Bubble graph for average CO emissions relating PKE, average speed and simulated emissions.

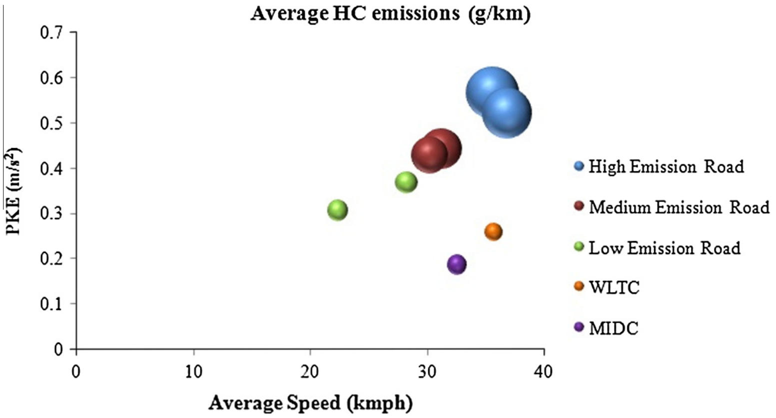

Fig. 17. Bubble graph for average HC emissions relating PKE, average speed and simulated emissions.

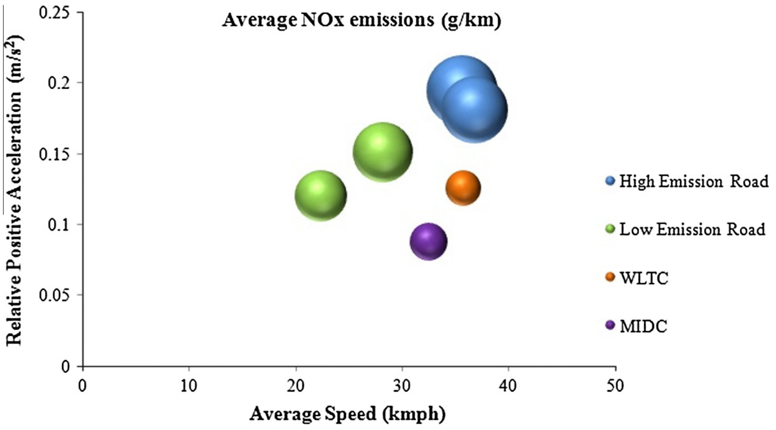

Fig. 18. Bubble graph for average NOx emissions relating RPA, average speed and simulated emission.

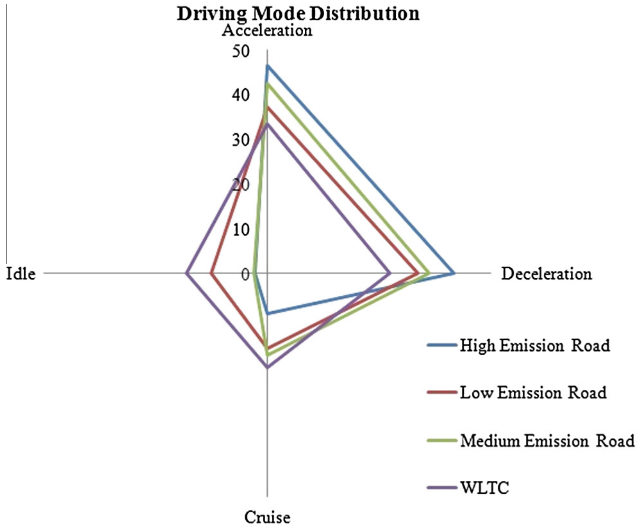

Fig. 19. Driving mode distribution for high, medium and low emission road cycle compared to WLTC.

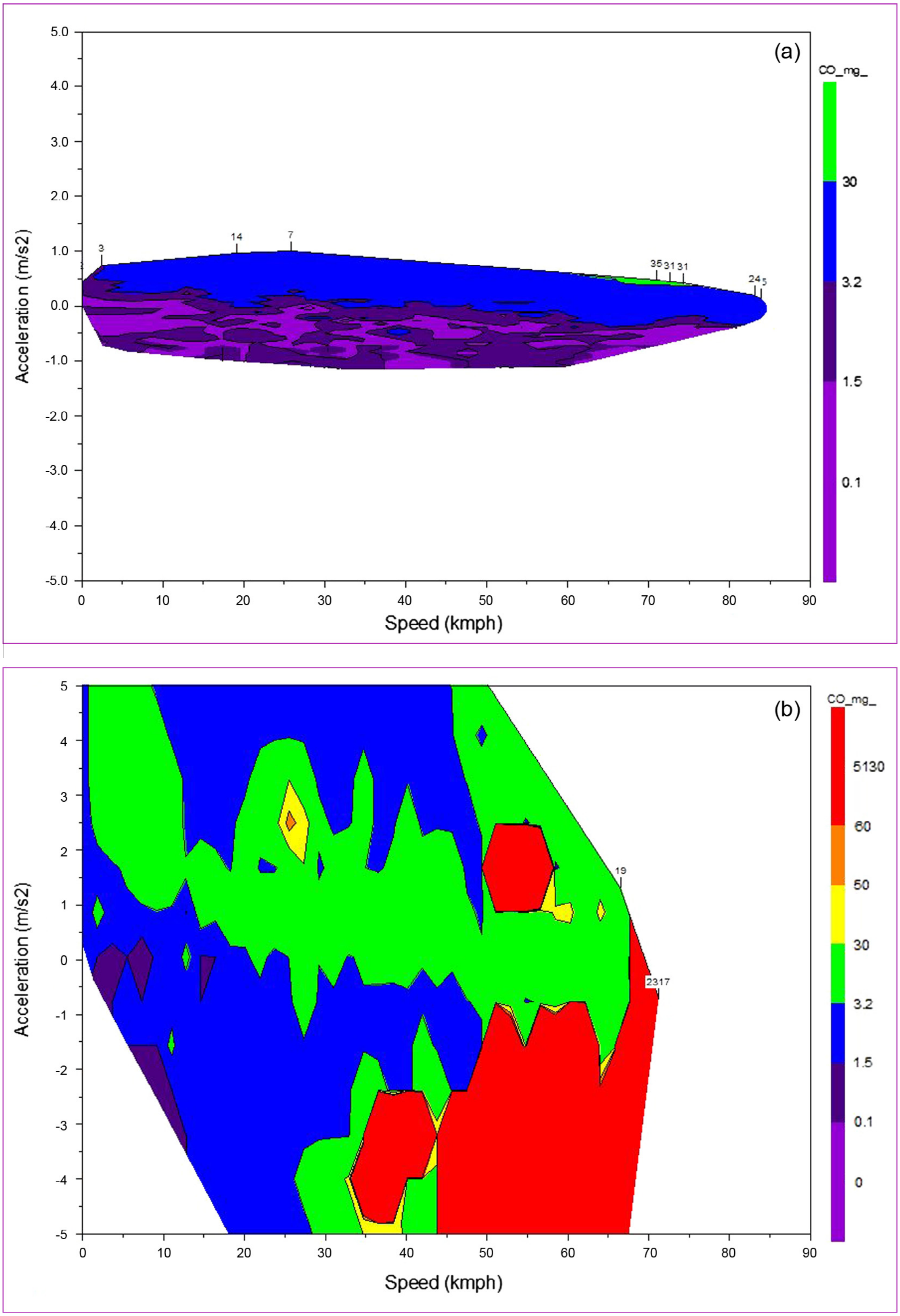

Fig. 20. Contour plots of instantaneous CO emission (mg/s) for (a) WLTC and (b) high emission cycle.

Although the definition of modes is slightly ambiguous, extensive studies have established correlation between every mode and emission levels (Kamble et al., 2009; Hung et al., 2007; Frey and Unal, 2002; Tsai et al., 2005). Fig. 19 compares percentage of driving time in each mode of driving (Acceleration, Deceleration, Idle and Cruise) for three representative road cycles, each respectively representing comparatively high, medium and low level of emissions on emission models.

Road cycles in general spend far more percentage of time in acceleration and deceleration modes. A high polluting road cycle is typically composed of 46% acceleration and 42% deceleration, whereas a low emission road cycles spends 37% time accelerating and 33% decelerating. In contrast, WLTC has roughly 33% in acceleration and 27% in deceleration.

Standard cycles spend significant time in cruise mode, roughly 21%. However, real world road patterns have very limited cruise time, ranging to 16% in low emissions and 9% in high emission patterns. Similarly, idle time in WLTC is significantly high, with roughly 18% of total time spent in idle mode. Whereas a high emitting road cycle spends less than 3% time idling. Medium emission cycle spends just a little above 3% time in idle mode and a low emission pattern constitutes roughly 12% idling.

Contour analysis

Apart from aggregate emissions and parameters, instantaneous analysis using CMEM simulation can be used to understand the basis of gaps between real world cycles and standard driving cycle. The effect of driving pattern distribution and its contribution to emissions can be visualized.

Fig. 20 compares instantaneous CO emissions of WLTC modelled on CMEM with a comparatively high emission real world road cycle. WLTC operates in a limited range of acceleration, though the speed ranges of both are similar. Very low emissions are observed at low speeds, whereas at higher speeds, even small accelerations cause significant CO emissions.

In WLTC, highest emissions occur in high speed, high acceleration zones. For the road cycle, high emissions are observed even at moderate speed and high accelerations. Very high emissions are also observed in road cycles at very high speeds and very large decelerations, suggestive of intensive braking at high speed. However, the acceleration is limited with increasing speeds, but areas with high speeds and high acceleration are predicted to have high emissions.

Conclusions

- The study evaluated the gap between driving patterns experienced by a light passenger car in a typical Tier-II Indian city and the standard test cycles.
- Simulated emissions for HC, CO and NOx for WLTC were respectively 0.77 g/km, 0.039 g/km and 0.22 g/km. The emissions in road cycles for same pollutants were respectively 155%, 63% and 64% higher.
- Among greenhouse emissions, $CO_2$was estimated to be 31% higher on road driving. However, toxics like benzene were simulated to be around 300% higher than the WLTC levels.
- Road cycles in Tier-II cities follow start–stop characteristics with sharp accelerations and braking, however, the average speed was low. WLTC has an average speed of 35 km/h, whereas, road cycles are up to 23% lower.
- WLTC estimated the maximum speed obtained on road reasonably well, howeverit was much smoother than road cycles. Road cycles spent up to 46% time accelerating and 42% decelerating, with much higher magnitudes of acceleration than WLTC.
- RMS acceleration of WLTC was estimated to be 0.13 m/s^2.RMS acceleration of road cycles are estimated 500% higher than WLTC, with 55% higher positive accelerations.
- Road cycles thus have roughly 100% higher energy demand in terms of PKE than WLTC, which has a PKE of 0.257 m/s^2
- Relative Positive Acceleration of WLTC is estimated to 0.13 m/s^2 road cycles exert loads 60% higher in terms of relative positive acceleration.
- The high accelerations are correlated with higher emissions in road conditions. Sharp braking at high speeds is responsible for higher emissions. Such high accelerations are not represented in standard cycles like WLTC.
- WLTC does not map all acceleration-speed bands, especially the high acceleration and braking phenomenon. For light passenger cars, this has a significant effect on total emissions when comparing this to the real driving data.
- MIDC, adopted from NEDC used for emissions regulation does not estimate emissions closely. However, moving to WLTC represents only a marginal improvement in emission predictions.

Scope of future work

The road driving cycles and different driving parameters can be used to create a more realistic driving cycle that represents conditions in Tier-II Indian cities more closely. This cycle can be used for laboratory testing for emissions and the data can be compared with emissions recorded form real world driving. From this analysis, it may be possible to fill the gap between real world driving cycles and WLTC.

Table A1
Representativity of different combinations of cycle parameters for emission factors.

Parameters	R^2 for emission factors		
	NOx	CO	HC
RPA, average speed	0.990	0.946	0.958
PKE, average speed	0.989	0.941	0.958
Average speed, average positive acceleration	0.957	0.928	0.959
% Cycle time idling, acceleration, deceleration, cruise	0.923	0.857	0.813
Average speed, STDEV (v)	0.823	0.879	0.951

Table A2
Driving mode definitions.

Mode	Speed	Acceleration
Idle	⩽5 km/h	–
Cruise	⩾5 km/h	⩾−0.1 m/s^2 and ⩽0.1 m/s^2
Acceleration	⩾5 km/h	>0.1 m/s^2
Deceleration	⩾5 km/h	<−0.1 m/s^2

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Appendix A. Cycle parameter definitions

$$\mathrm{PKE} = \frac{\sum(v_f^2 - v_s^2),\ \forall \frac{dv}{dt} > 0}{x}$$

$$\mathrm{RPA} = \frac{\frac{1}{T}\int_0^T (v_i \times a_i^+)dt}{\bar{v}}$$

$$\text{RMS Acceleration} = \sqrt{\frac{1}{T}\int_0^T (a^2)dt}$$

where v_f, final speed for acceleration sequence; v_s, starting speed for acceleration sequence; x, total distance travelled; t, time; T, total operational time; v_i, initial actual speed; a_i^+, positive acceleration; and a, acceleration (see Tables A1 and A2).

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