International Journal for Traffic and Transport Engineering, 2016, 6(3): 265 - 279

DOI: http://dx.doi.org/10.7708/ijtte.2016.6(3).03 *UDC: 621.43.068(540)*

DEVELOPING SPEED DEPENDENT EMISSION FACTORS USING ON-BOARD EMISSION MEASURING EQUIPMENT IN INDIA

Sushant Sharma[1], Tom V Mathew[2]

[1] *Texas A&M Transportation Institute, Texas A&M University, USA*

[2] *Indian Institute of Technology Bombay, Mumbai, India*

Received 1 April 2016; accepted 22 July 2016

Abstract: Vehicular emission models are important tools in several environmental impact studies. Although several studies have been conducted for emission control purposes, few attempts have been made on the planning side. For instance, long-term transportation network capacity improvement models do not explicitly consider emission in the objective function. Incorporating vehicular emission into the objective function is effective only if speed dependent emission factor is used in the estimation of emission. Although this issue is well addressed in the developed countries, owing to the heterogeneity of vehicles and absence of speed dependent emission factors the benefit from network investment is often underestimated in developing countries like India. Therefore, an attempt is made to explore the possibility of developing speed dependent emission factor for Indian conditions and vehicles. For accurate measurement an onboard test is conducted on typical vehicles; namely, a passenger car, a sports utility vehicle, and a truck. On board test equipment collected the data while the vehicle traversed with different speed ranges. The data obtained is processed and used for developing emission factor in the form of second degree polynomial with speed as the dependent variable. The emission factors for the three types of vehicles and for CO, CO_2, NO_X, and HC are developed. The results have been compared with Indian driving cycle based emission factors as well as UK based speed dependent emission factors for car in particular. The study gave a preliminary insight into the behaviors of pollutants with respect to speed. However, there is a need to develop such factor using large spectrum of vehicles and diverse driving conditions.

Keywords: vehicle emission, on-board emission measurement, speed dependent emission factors.

1. Introduction

Vehicular emission models are important tools in several environmental impact studies. These models help in understanding and quantifying the environmental impact of transportation projects. The most common approach is the quantification of emission from the vehicle miles traveled and a constant emission factors. These emission factors are developed based on the driving cycle derived from the existing traffic pattern in the area of interest. A driving cycle is a time series of vehicle speeds recorded at successive equally spaced time points supposedly representing the driving pattern for the region. Vehicles

[1] Corresponding author: s-sharma@tamu.edu

are kept under controlled condition over a chassis dynamometer and then run according to profile of the driving cycle. The emission factors derived based on the driving cycle are usually some constant values, represented as the amount of pollutant per kilometer or mile traveled by the vehicle.

The derivation and the use of constant emission factors have several of limitations. First, obtaining driving cycle and testing in a chassis dynamometer is a prohibitively expensive test procedure. Therefore, these factors are not frequently updated with the changing vehicle technology and more importantly the driving pattern. Second, in most of the cases, driving cycles are developed for a whole country (e.g. Indian driving cycle) or even for a continent (e.g. European driving cycle). Note that such driving cycles are needed for vehicle certification purpose and were predominantly used by vehicle manufactures and motor vehicle department. Their objective is that vehicles need to meet certain emission norms which have to be uniform across the country. For this purpose, there has to be only a single driving cycle, even for large country like India. However, the temporal variations between the cities or regions with in a large metropolis are usually ignored. The current practice in countries like India is to derive constant emission factor using simple driving cycle on chassis dynamometer. The constant emission factors are not suitable especially in the context of assessing changes in emissions due to transport infrastructure projects. For example, typical transportation planning is accomplished using the classical four step travel demand modeling, namely trip generation, trip distribution, model split, and traffic assignment. One of the outputs from the traffic assignment module has the vehicle kilometers or miles traveled. From the vehicle kilometers traveled and the constant emission factor, one could calculate the emission. However, this may lead to unexpected results. For instance, if for a given demand the vehicle kilometer is computed based on the traffic before and after expansion, then the vehicle kilometer traversed may be higher in the latter case. The value of emission will obviously be higher after the expansion. This is counter intuitive and points to the deficiency in the modeling. What this modeling approach failed to consider is the improved speeds in the network. A better alternative is to incorporate the effect of change in the speed in the emission estimations. It may be noted that, the traffic assignment models will give the average link speed in addition to the vehicle kilometers. Therefore, without any additional analysis, one can get the link speed as well as vehicles kilometers traveled simultaneously. Therefore, there is a need to develop and use a speed dependent emission factor which can utilize both speed and vehicle kilometer. This will provide better estimate of emission. Since the behavior of pollutants vary with the speed, it may be also possible that some pollutant may even increase after expansion. Finally, the expansion problems usually identify the links and the amount of expansion by minimizing the travel time. However, if a speed dependent emission factor is available, then one could design the network even purely minimizing the emission (Sharma and Mathew, 2011). Such an exercise will have significant contribution to the green house gas reduction.

2. Literature Review

The review of the past studies on the practices of emission models, attempts to develop speed dependent emission factors, and the status of the emission modeling in India is presented below. First emission factors currently used is presented in this section. In United States the current practice is to use MOVES model. MOVES is an U.S. Environmental Protection Agency (USEPA) model for estimating pollution from highway vehicles. The model accounts for the emission impacts of factors such as changes in vehicle emission standards, changes in vehicle populations and activity, and variation in local conditions such as temperature, humidity and fuel quality. In addition, EMFAC7F model developed by the California Air Resources Board (CARB) is also being used to account for travel related, weather related and vehicle related emissions.

In early 2000s, several studies were conducted to develop speed dependent emission factors. Ahn et al. (2002) developed several regression models that predict emission rates for light duty vehicles. In addition they also claimed that if the model utilizes the vehicles instantaneous speed and acceleration levels as independent variables, then the models are capable of evaluating environmental impacts of operational level projects including Intelligent Transportation Systems. El-Shawarby et al. (2005) evaluated the impact of vehicle cruise speed and acceleration levels on vehicle fuel consumption and emission rates using filed data gathered under real world driving conditions and validated the VT-Micro model for modeling in real world traffic conditions. Yu (1998) developed ONROAD vehicle exhaust model for estimation of CO and HC emissions to evaluate various traffic control and management strategies. Younglove et al. (2005) considered various issues associated with on road emission measurement and modeling and suggested measures to reduce measurement error. André and Hammarström (2000) showed the sensitivity of pollutant emissions as regards the driving speed using the emission functions currently available from the literature. They carried out survey throughout Europe and proposed realistic speed ranges for the various categories of vehicles and situations. Sbyati et al. (2002) investigated the three levels of network aggregation, macro scale, meso scale and micro scale on emission inventories. This study suggested that the choice of link by link estimations of emission depends on the complexity of the network and type of study. For complex networks, the link-by-link approach is recommended to evaluate emission patterns, but for simpler networks, the roadway functional class basis or even the overall – average approach may be adequate. Chan et al. (2004) studied on road petrol vehicle emission of carbon monoxide, hydrocarbon and nitric oxide at nine sites in Hong Kong. Their results show that petrol vehicle model year, engine size and driving patterns have a strong correlation on their emission factors. Ding and Rakha (2002) demonstrated that average speed and speed variability were two critical variables for estimating vehicle fuel consumption and emission rates. Tong et al. (2000) reported the analysis of on-road vehicle speed, emission, and fuel consumption data collected by four instrumented vehicles. Time-, distance-, and fuel-based average fuel consumption, as well as CO, HC, NOx, and soot emission factors, were derived. The influences of instantaneous vehicle speed on emissions and fuel consumption were studied. It was found that the fuel-based emission factors varied much less than the time and distance based emission factors as instantaneous speed changed. Furthermore, it was found that the transient driving modes (i.e., acceleration and deceleration) were more polluting than the steady-speed driving modes (i.e., cruising and idling) in terms of g/km and g/sec. These results indicated that the on-road emission measurement is feasible in deriving vehicle emissions and fuel consumption factors in urban driving conditions. Pelksmans and Debal (2006) showed the emission levels measured by European Drive cycle can be very different from the emissions produced in real traffic. They showed in their study that model year 2000 vehicles which complied EURO 4 limits may reach CO and NOx emission that may be up to 10 times higher in real traffic conditions compared to New European Driving cycle.

A brief review of the emission modeling in India is presented here. Indian driving cycle (IDC) was formulated around late 1985, after extensive road tests by the scientists at the automotive research association of India, Pune, when the mass emission norms were enforced. Since the IDC involves too many transients because of haphazard traffic situations in India, this is now only followed for two/three wheelers, which are common modes of transportation in Indian cities. For passenger cars, a modified European driving cycle, by providing a correction for a lower maximum speed, is followed and is called the Indian driving cycle. The driving cycle is used to develop constant emission factor by performing chassis dynamometer test. In India till now only driving cycle based emission factors are used. Several emission factors for Indian vehicle can be found in studies by agencies like Central Pollution Control Board of India (CPCB, 2010), Indian Institute of Petroleum (Pundir and Das, 1985) and Automotive Research Association of India (Pundir et al., 1994) , and Government of India (AFP, 2015). Emission factors for Indian vehicles have also been reported by Luhar and Patil (1986); Bose (1998); Sharma et al. (2002); Mittal and Sharma (2003), and Gurjar et al. (2004). Mittal and Sharma (2003) made an effort to look at India's present and projected emission inventory by studying the transport and distribution patterns of emitted pollutants and by developing a long-term air quality database covering the country's various geographical areas. In the study they have presented speed varying emission factor based on driving cycle and not in real traffic conditions. Study by Gurjar et al. (2004) may be considered as the first comprehensive and consistent emission inventory for Delhi, India which included a range of air pollutants and greenhouse gases. They also developed emission factors which were based on laboratory measurements and compiled data from previous studies including uncontrolled data from Europe or United States of America. The emission function is adopted from European Environment Agency and modified to suit emission from the Delhi traffic. Mehta et al. (2006) developed a rigorous emission model considering speed dependent emission factors by using the model developed by National Atmospheric Emission Inventory (NAEI) of United Kingdom. Although the model is claimed to be specific to Indian traffic condition, it uses speed dependent emission factor from UK and adjusted for a local traffic conditions. A recent study by Kamble et al. (2009) developed a driving cycle for an Indian city which is significantly different from the standard driving cycle characterized by high acceleration and deceleration values. Although such driving cycle is considered to be a better representation of the driving pattern of the city, however, developing emission factors using chassis dynamometer is not feasible because of steep acceleration and deceleration unless the equipment has sophisticated instrumentation. A study by Bokare and Maurya (2013) in India captured tailpipe emission rate for small cars, however study did not go beyond one type of small car. A recent study by Ramachandra et al. (2015) in India highlight the significant changes in land cover with the decline in vegetation, water bodies, crop and fallow land that necessitates an integrated approaches in urban planning to ensure the environment sustenance. The study recommends that government needs to play a pivotal role in planning sustainable cities with the healthy urban environment. However, lack of speed dependent emission factors for various modes that can help model emissions against infrastructure development is an issue that has not been addressed.

It can be concluded from the above review that constant emission factors may not be able to model accurately the impact of long range transport improvements and accurate emission model depend on the consideration of traffic variables such as instantaneous speed, acceleration, and deceleration. Further, on road emission measurement is able to give emission in actual driving conditions. In addition, it is comparatively cheaper than chassis dynamometer and can be performed on different vehicles including the heavy duty vehicles irrespective of the locations. It also provides a wide variety of data like grade, location, throttle, engine temperature, etc. Therefore, on-road emission measurements could be a better alternative to dynamometer based experiments to develop emission factors. Speed dependent emission factors are not yet developed for Indian traffic conditions which has vide variability in speed and heterogeneous mix of traffic. Further, transportation infrastructure design will not be able to account for accurate emissions without such emission factors.

3. Methodology

The objective of the present study is to develop speed dependent emission factors using On-board emission measuring instrument. The vehicle is run at different speed ranges for a long stretch of road with almost same gradient and less traffic. This test has been performed typically on three type of vehicles commonly used in India. Two wheelers could not be explored due to the limitation of the on-board machine sensors. This is an exploratory study and is first of its kind in India. In developing this model we have ignored variation in the distribution of vehicle type, age, make and are left as a scope for future investigations. Instead, three representative vehicles are considered. It may be noted that in this study the effect of acceleration/deceleration is considered only implicitly. The reason being several planning studies are done at macro level, which does not require the effect of acceleration/deceleration to be considered. For example, network design problems like capacity expansion problems, signal settings, optimal tolls etc. This study was done with the objective of further using the derived speed dependent emission factors for a network design problem.

3.1. On Board Test Setup / Data Acquisition

The instrument used for on-board data collection in this study is the OEM-2100™ manufactured by Clean Air Technologies International, Inc. The system is comprised of a five-gas analyzer, an engine sensory array and an on-board computer. OEM–2100 is designed for measuring vehicles exhaust emissions under actual on-road conditions. This system is designed to work with all internal combustion engines, and the studies on different vehicles have been done to ensure its efficacy. It provides second by second data of emissions, fuel consumption, vehicle speed, and engine parameters like engine rpm temperature, manifold air pressure and many other details.

Fig. 1.
On Board Emission Setup in a Vehicle

3.2. Calibration of the Instrument

The OEM-2100TM is calibrated on a routine basis using a calibration gas. For this purpose, a calibration gas that has a composition of 6.3 percent CO, 12.18 percent CO2, and balance Nitrogen, 3120 ppm Propane, and 2990 ppm NO is used. In the calibration process, the calibration gas is measured by the OEM-2100. If the measured values differ significantly from the known true values, then the OEM-2100 is calibrated with respect to the calibration gas. The calibration process has been repeated approximately every 3 months.

3.3. Experimental Setup

The experiment was designed to suit the field condition to the maximum possible extent. A uniform stretch from a freeway having very less traffic was chosen. There is no significant variation in the gradient of the selected stretch. The length of the stretch was about 6 km long and has four lanes in each direction. The test vehicles were run on the same stretch. The vehicle was driven by same driver for all days of experiment so as to minimize the error due driving behaviour. Each time the vehicle was started one hour before the experiment to bring it to hot stabilized mode. The experiments were normally done when the least traffic was expected on the roads. The vehicles were run usually on the outer lanes. The vehicles were run at different speed ranges for almost two kilometer on the stretch and then switched to the next speed range. Three runs were made in each speed category to increase precision of the data collected. The reason for performing the test at the steady speeds is to accurately capture the emissions at various speed levels, our objective of this study is to develop only speed dependent emission factor. Moreover, the On board emission testing machine is very sensitive to acceleration and deceleration and large amount of data is required to account for such variability. The details of the experiment performed are given in the Table 1. The emission capturing from SUV and Truck have not been attempted at the speed of 10 Km/hr because of the difficulty in maintaining that particular speed in case of both vehicles. The on-board emission testing equipment automatically logs the emission details and an in-built GPS instrument captured instantaneous speed of the vehicles.

Table 1

Experimental Plan for the on-Board Testing

Vehicle Type And Fuel	Speed Km/h	Distance Km	No. of Runs
CAR: Omni Car/Van Gasoline Driven 796 cc Engine	10±2	2 km	3
	20±2	2 km	3
	30±2	2 km	3
	40±2	2 km	3
	50±2	2 km	3
	60±2	2 km	3
SUV: Sumo – Sports Utility Vehicle Diesel Driven Engine 1948 cc	20±2	2 km	3
	30±2	2 km	3
	40±2	2 km	3
	50±2	2 km	3
	60±2	2 km	3
TRUCK: Tata Truck 1613C Diesel Driven Engine 5883cc Turbocharged	20±2	2 km	3
	30±2	2 km	3
	40±2	2 km	3
	50±2	2 km	3
	60±2	2 km	3

4. Data Analysis

4.1. Data Obtained

A typical example of data obtained by the experiment is presented in the Table 2. The table shows parameters that are obtained by on-board emission measuring equipment. The parameters include the time in seconds, speed in kmph, acceleration in km per hour per second, NOx, HC, CO, CO_2, O_2, PM, Gradient, GPS longitude, latitude, engine RPM., sensed temperature, throttle, torque in lbf, intake air in g/s, dry exhaust in g/s, total exhaust flow, and fuel consumption rate. Pollutants were measured in ppm, grams/second and grams per kilometer. Due to space constraint only a few parameters are being presented in the table.

4.2. Data Cleaning

There was difficulty for the driver to maintain a constant speed for long time (no cruise controls were available). Therefore, there was occasional variation in the speed although it was within a small range of ±2 kmph. Since the objective of the experiments was to measure the variation in emissions with speed, the data was first cleaned manually by discarding the observations if there is any acceleration at that moment.

Then the absurd values of emission like negative values were also removed from the data set. The outliers were also removed directly as they were quite distinct and might have been caused by experimental errors beyond anyone's control. In some of the cases, the outliers were the starting points before reaching the stabilized mode of the vehicle. In few cases the speed were fluctuating significantly in short intervals. These measurements were also eliminated.

4.3. Curve Fitting

The cleaned data was then used for developing the emission functions. The Curve Fitting Tool in MATLAB was used to fit the curves. The data was fitted by using quadratic polynomial function and validated by obtaining various goodness of fit. Since graphical fits are highly subjective, numerical fit with a goodness of fit statistics is preferred. The results of the curve fitting with emission factor as independent variable and speed as a dependent variable is developed. A linear polynomial model of the form:

$$\mathbf{f(x) = a\, x^2 + b\, x + c} \qquad (1)$$

where f(x) is speed dependent emission factor as a function of speed *x*; and *a*, *b*, and *c* are the coefficients of regression equation.

Table 2

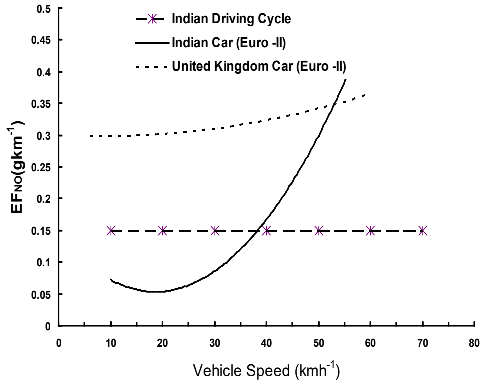
A Sample of Output from on Board Emission Testing Equipment

Time [s]	km/h	accel [km/h/s]	No_x [ppm]	HC [ppm]	NOx [g/s]	HC [g/s]	CO [g/s]	CO_2 [g/s]	PM [mg/s]	NO_x [g/km]	HC [g/km]	CO [g/km]	CO_2 [g/km]
38192	43	1	295	213	0.005	0.007	0.42	1.95	0.020	0.41	0.55	35	162.90
38193	45	2	352	232	0.006	0.007	0.45	2.01	0.030	0.48	0.59	36	160.70
38194	47	2	374	232	0.007	0.008	0.41	2.13	0.030	0.51	0.60	31	163.10
38195	48	1	439	229	0.008	0.008	0.37	2.25	0.020	0.61	0.60	27	168.70
38196	50	2	548	225	0.010	0.008	0.38	2.32	0.020	0.75	0.58	27	167.30
38197	51	1	600	200	0.012	0.007	0.37	2.44	0.020	0.85	0.53	25	171.90
38198	53	2	610	247	0.013	0.010	0.36	2.49	0.020	0.86	0.65	24	168.80
38199	55	2	541	273	0.011	0.011	0.49	2.37	0.030	0.73	0.69	32	155.19
38200	55	0	430	247	0.009	0.010	0.59	2.25	0.030	0.61	0.65	38	147.30
38201	55	0	339	228	0.008	0.010	0.52	2.28	0.030	0.52	0.66	33	148.90
38202	55	0	255	211	0.005	0.008	0.36	2.31	0.020	0.35	0.54	23	151.50
38203	55	0	315	395	0.007	0.016	0.52	2.31	0.040	0.43	1.02	33	151.00

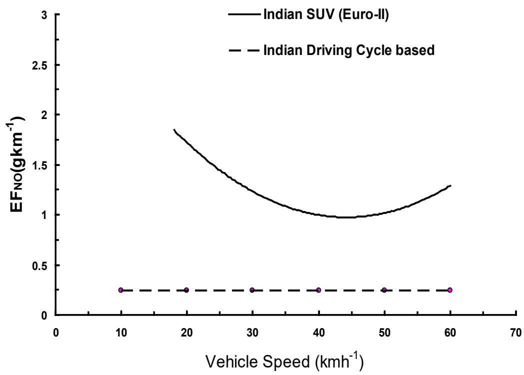
Table 3

Results of Curve Fitting with Second Degree Polynomial of Emission Factor with Speed as the Dependent Variable with the Measure of Errors

Pollutant	**Vehicle**	**Coefficients**		
		a	b	c
NO_x	CAR	0.000249	-0.00933	0.1405
	SUV	0.001264	-0.1118	3.448
	TRUCK	0.006815	-0.8451	27.55
CO	CAR	0.0029	-0.288	10
	SUV	0.001679	-0.1611	3.957
	TRUCK	0.0002483	-0.04091	1.698
HC	CAR	0.0002	-0.211	0.6974
	SUV	0.0006109	-0.05325	1.384
	TRUCK	0.0001957	-0.02933	1.139
CO_2	CAR	0.5957	-50.71	1221
	SUV	0.4979	-39.77	1074



(a)



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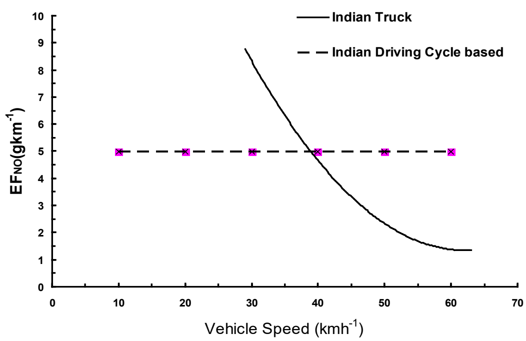
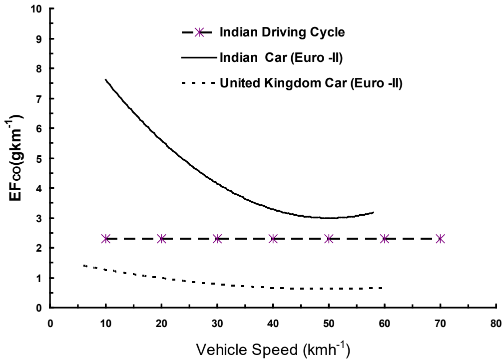


(c)

Fig. 2.
Comparison of Developed Speed Dependent Emission Factors for NO_X (Car, SUV, Truck) with Constant Value Indian Driving Cycle Based Emission Factors and UK Speed Dependent Emission Factors for Car



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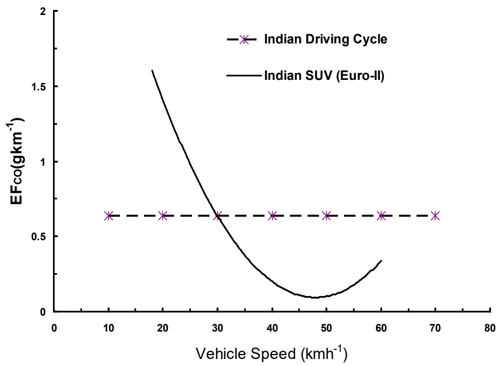

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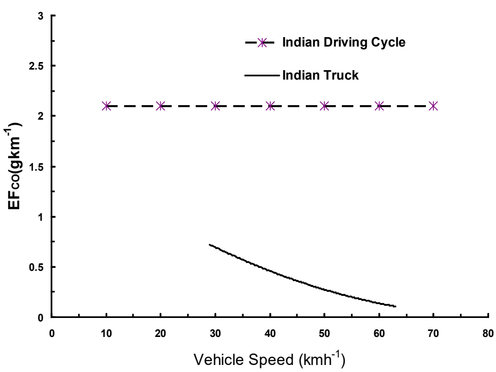
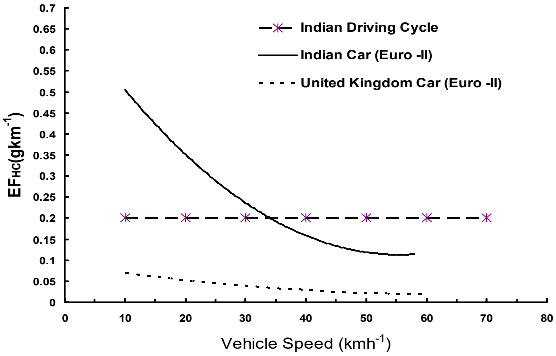
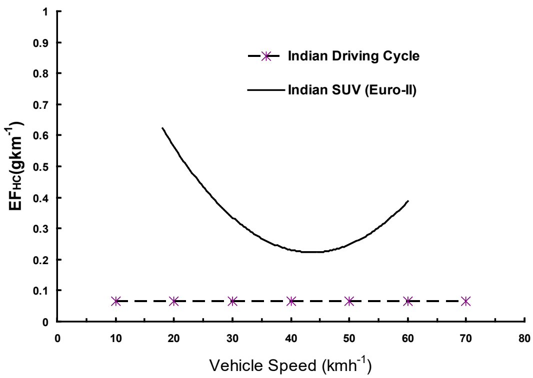


(c)

Fig. 3.
Comparison of Speed Dependent Emission Factors for CO (Car, SUV, Truck) with Constant Value Indian Driving Cycle Based Emission Factors and UK Speed Dependent Emission Factors for Car



(a)



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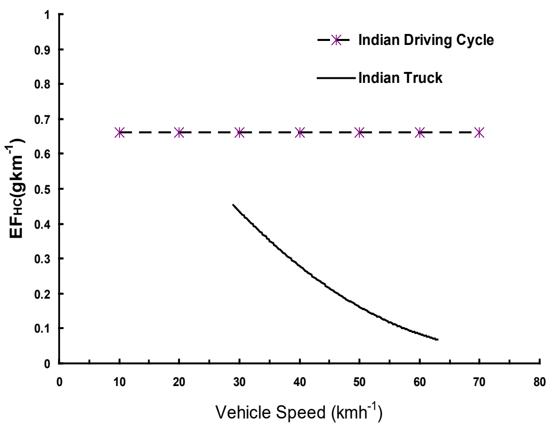

(c)

Fig. 4.

Comparison of Speed Dependent Emission Factors for HC (Car, SUV, Truck) with Constant Value Indian Driving Cycle Based Emission Factors for Car

4.4. Discussion of Results

The coefficients of emission functions for SUV, car, and truck are presented in Table 3. The correlation found among various functions for the pollutants were found satisfactory by considering experimental errors with R-square between 0.32 (least for emission factor of CO in car) to 0.95 (CO_2 in car). The plots of the emission functions for SUV, car, and truck along with vehicle speed for NOx, CO and HC are shown in Figs. 2, 3 and 4 respectively. The comparison of developed speed dependent emission factors have been made with Indian driving cycle based emission factor for all the categories of vehicle and UK based speed dependent emission factor for car following norms. The reason of comparing with UK based speed dependent emission factor is that the Indian driving cycle (IDC) is based on European standards and therefore can be considered as the benchmark for comparison. Fig. 2a shows the comparison of emission factor for pollutant NOx for Car with both Indian driving cycle based emission factor and UK based speed dependent emission factor for Car. The graph shows the developed emission factor significantly underestimates as compared to UK based model. The developed emission factor value reaches equal to Indian driving cycle based constant emission factor (0.15 gm/Km) at the speed of 37 Kmph. The Indian driving cycle is developed for urban arterial speed of 30-35 Kmph and this converging of developed emission factor value shows a good prediction by model. The comparison for SUV shows that the driving cycle based emission factor fairly underestimates the NOx emissions whereas for truck the constant emission factor value from IDC is reached by the developed speed dependent emission at speed 40 Kmph. Fig. 3 shows the emission factor developed for CO for various types of vehicles and its comparison among IDC based constant emission factor value and UK based emission factor for CO for car (Fig. 3a). The curves in Fig. 3a shows that the developed model is slightly higher that the IDC based emission factor throughout all speed levels, whereas is fairly high as compared to UK based speed dependent emission factor. It shows that Indian vehicles might be more producing more CO than the UK vehicles given to driving condition, engine maintenance etc. In case of SUV the speed dependent emission factor reaches a value equal to IDC based emission factor at the speed of 30 Kmph again validating the result from developed model. The IDC based emission factor for the truck (Fig. 3c) is fairly high, although the comparison may not be proper as most of the data used after cleaning for developing speed dependent emission factor for truck was for speed intervals between 30 Kmph to 65 Kmph. Fig. 4 shows the comparison among emission factors for the pollutant HC. The comparison of curves for car shows the developed model reaches the value of IDC based emission factor at speed 30 Kmph, which is average speed of driving cycle and further endorses the ability of model to correctly predict the emission of HC. The comparison with UK based speed dependent emission factor for car is done in Fig. 4a. The values again are much higher than UK based emission factor for car. In case of SUV the developed emission factor show a convex shape of curve with least emission at 40 Kmph, whereas the IDC based emission factor still lies below this value. In case of truck, the developed model can be considered to be under predicting as compared to IDC based emission factor.

5. Conclusion

Transportation network planning models considering environmental parameters need to incorporate the effect of speed improvements in the vehicular emissions. Although constant emission factors are still widely used in many countries like India, only speed dependent emission factors can capture changes in emission due to transport network and infrastructure improvements. Emission factors are traditionally obtained from chassis dynamometer experiments using driving cycle, which in turn is constructed from the traffic characteristics. An alternative to this costly and indirect experiment is the use of on-board emission measurement. In the present study, an attempt is made to develop speed dependent emission factors using data from the real traffic conditions in India. Three test vehicles, namely a car, a SUV, and a truck, were considered for the study. Emission models were developed for the pollutants that contribute significantly to the transport sector, namely NOx, CO, CO2, and HC. The emission factors were developed as second degree polynomial functions of speed. The speed and the emissions showed strong correlation. The emission factor models were compared with Indian Driving cycle based constant emission factors. In addition, the model was also compared with UK based speed dependent emission factor for Car norms. The results indicate that the emission are higher that the European in most of the cases. The trend is similar for Indian driving cycle except for trucks. Although this study is limited to three vehicles, it is important to note the advantage of on-board equipment as well as the significant differences is the emission from the driving cycle based emission factors. Therefore, the study suggests the need for developing emission factors from extensive on board experiments rather than driving cycle-chassis dynamometer based indirect experiments. The study results will be used to model the emissions from various infrastructure improvement projects based on increased mobility in terms of speed. For example, in recent research (Torok, 2015) showed using available emission factors showed that Monte Carlo simulation are suitable for the assessment of regional transport and environmental policy incentives.

Acknowledgement

The authors would like to thank Department of Civil Engineering, IIT Bombay, India and Industrial Research and Consultancy Center, IIT Bombay, India for providing financial support for the experiments and Central Road Research Institute, India for their cooperation in carrying out the experiments.

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