Transportation Research Part D 43 (2016) 59–70

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Urban real-world driving traffic emissions during interruption and congestion

Arti Choudhary, Sharad Gokhale *

Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

A R T I C L E   I N F O

Article history:
Available online 7 January 2016

Keywords:
Urban traffic flow
Stop and go
Peak hour
Mileage
Instantaneous speed
Emission factor

A B S T R A C T

On-road emissions from urban traffic during interrupted and congested flow conditions are too high as compared to free-flow condition and often influenced by accelerating and decelerating speed due to frequent stop-and-go. In this study, we measured emissions from passenger cars and auto-rickshaws during peak and off-peak hours and analyzed according to different mileages with the instantaneous speed and acceleration for interrupted and congested traffic conditions. It was found that during flow, several short-events lasting over fractions of a second each lead to a sharp increase in pollutant emissions, indicating episodic conditions. The emission levels are sensitive to frequency and intensity of acceleration and deceleration, in accordance with the traffic-flow patterns and speed, besides mileages. Further, congestion conditions occur during both peak and off-peak hours, but last for different durations. The results are important in the sense that instantaneous estimates of pollutant emissions are necessary for the assessment of air quality in urban centers and for an effective traffic management plan.

Introduction

Passenger cars make up a major portion of traffic fleets on urban roads (Shukla and Alam, 2010). Rapid growth and expansion of urban centers increase traffic demand, which in most cities have exceeded the road capacities, and a major cause of frequent congestion events. Traffic congestion events are severe particularly the times when people by virtue of workplaces, schools and other commercial activities crowd in urban centers, causing excess transport demand. During such crowded times, interaction between vehicles and between vehicles and people increases, which reduces the overall speed of the traffic flow causing congestion (Gakenheimer, 2002). Vehicles, when encounter frequent stop-and-go, increase commuting time, fuel consumption and pollutant emissions. Pollutants emitted from vehicular exhausts – carbon monoxide (CO), hydrocarbon (HC), oxides of nitrogen (NO_x) and fine particulate matter (PM), are associated with vehicle types and fuels used. Besides, road traffic also contributes to greenhouse gases such as carbon dioxide (CO_2).

The share of passenger cars and auto-rickshaws on urban roads is high in developing countries; the numbers of trips in urban centers are also high in comparison to other personalized vehicles. For example, one auto-rickshaw in New Delhi travels on average 150 km daily (Reynolds et al., 2011). Auto-rickshaws are important hire-transport vehicles in most Asian cities. Auto-rickshaws with 2-stroke engines consume about 20% more fuel and emit more CO_2 emissions compared to 4-stroke engines (Reynolds et al., 2011). Ramachandra (2009) and Singh (2006) reported that annual utilization of cars and

* Corresponding author. Tel.: +91 361 258 2419; fax: +91 361 258 2440.
E-mail address: sharadbg@iitg.ernet.in (S. Gokhale).

http://dx.doi.org/10.1016/j.trd.2015.12.006

taxis is higher than two-wheelers, almost double, i.e. 12,600 km as compared with the 6300 km of two-wheelers, in India. Li (2011) found CO_2 emissions in gasoline passenger cars high as compared to other transport modes.

Vehicles in metropolises of India contribute about 70% of CO, 50% of HC and 30–40% of NO_x (CPCB, 2006). De Vlieger et al. (2000) demonstrated that during rush hours, fuel consumption increases by 10% and emissions of CO, HC and NO_x emitted from passenger cars increase by up to 20% compared to during non-rush hours. Emissions also vary with vehicle and road types. A few studies have analyzed environmental benefits of specific road geometry in terms of vehicle delay, number of stops and duration of stops (Guerrieri et al., 2015; Tollazzi et al., 2015). Road geometry and type also influence the number of acceleration/deceleration cycles and time spent in idling and therefore have significant impacts on fuel consumption and exhaust emissions (Pandian et al., 2009; Gokhale, 2012). Li et al. (2004) have studied signal timing model to reduce vehicle delays, fuel consumptions and emissions at traffic intersections. Further, several studies, which carried out on-board measurements of CO, HC, and NO_x, found that sharp accelerating peaks produce higher emissions and sometimes single sharp acceleration causes emissions higher than even an overall trip (Frey et al., 2001, 2003; Guensler, 1993; Bachman, 1998; De Haan and Keller, 2000).

Shukla and Alam (2010) studied the relationship of traffic and emissions by testing one light-duty-petrol-driven passenger car of 69,000 km mileage in a dynamic urban traffic condition in Delhi. They found high emissions during accelerations. Another study of Zhang et al. (2011) compared the work zone and rush-hour congestion with free-flow traffic and found high emissions during the transitional phase, when traffic-flow changed from free to congested condition. The study, however, used speed–acceleration profiles by car floating technique, which represents an average scenario of a limited number of vehicles on roads and may be underestimating actual emissions. Chen et al. (2007) carried out a study on nine heavy-duty diesel vehicles and reported that low speed with frequent acceleration and deceleration, particularly in congested conditions, are the main factors that aggravate vehicle emissions and cause high emissions of CO and HC. The emission levels depend heavily on traffic-flow characteristics, such as average flow speed, the frequency and intensity of vehicle acceleration and deceleration, the number of stops, and vehicle operating mode (Faiz et al., 1996). Episodic effects of emissions, caused by short-events, may be important consideration therefore for short-term near-road human exposure assessment (Zhai et al., 2008).

While most studies analyze emissions based on the chassis-dynamometer tests which reflect only a subset of real-world driving conditions, this study carried out the real-world on-road instantaneous measurements of speeds and exhaust emissions from light-duty-petrol-driven passenger cars and auto-rickshaws (a 3-wheeler passenger vehicle) with different mileages traveled in different traffic-flow patterns. Passenger cars and auto-rickshaws are the highly used road transport modes with the highest daily trips in urbanized cities compared to other transportation modes. The aim of this study, therefore, has been to evaluate the effect of different traffic-flow patterns and short-events on speed, acceleration, travel time and concomitant instantaneous pollutant emissions.

Experimental method

The study includes the real-world measurements of instantaneous speed, acceleration and tailpipe emissions of passenger cars and auto-rickshaws of different mileages on a highly trafficked urban road of Guwahati, one of the fastest growing cities in the North-East of India. A detailed traffic count was done on the road at two points of the test runs (Fig. 1a) during both peak hour (PH) and off-peak hour (OPH) with the help of videotapes. For traffic count, videotapes of 100 m stretch on the road were analyzed and speed and travel time of different category vehicles were estimated every 5 min over the same 100 m stretch. Robertson (1994) has also analyzed traffic data at 5 min intervals. Fig. 1b shows the section of road with a traffic scenario captured at camera point 1 during a peak hour. The stretch of the test run was 3.8 km long, double-lane (for two-way traffic) 16 m wide. It consists of a signalized intersection near camera point 2 and an unsignalized U-turn under the flyover near camera point 1. The measurements were carried out during different timings of the day, PH and OPH and on different working days of March 2014. The average traffic flow on the test route during OPH and PH was about 2590 ± 326 and 9368 ± 265, respectively. In the traffic fleet, the average share of two and four-wheelers (2W and 4W) was 87%, followed by 9–10% of three-wheeler (3W) and 3–4% of buses. During OPH, the share of 4W and 2W was 52% and 28%, respectively, while during PH, it was 34%, and 53%, respectively. The average fleet speed during OPH and PH was 46.84 ± 8.83 km/h and 20.26 ± 3.64 km/h, respectively.

The free, interrupted, congested traffic-flow patterns were identified (defined based on traffic video analysis), the proportion of the time traffic spends in each pattern was estimated, and impacts of speed, acceleration in PH and OPH were evaluated, particularly, in interrupted flow condition. These data were utilized to determine various traffic characteristics such as, percentage share of vehicle types, traffic-flow patterns and percentage of the time traffic spends in different traffic-flow patterns. Traffic volume observed at the site during the week and weekend days had a major share of passenger cars and auto-rickshaws. Therefore, these two categories of vehicles, which are gasoline-powered with different mileages traveled, were selected for the study. Table 1 shows the vehicle specifications and mileages used for emission tests. The auto-rickshaws are of the same weight while the passenger cars vary slightly in weights, which however may not impact the emissions significantly because they are gasoline driven. A few studies have reported that vehicle weight is one of the characteristics that influence emissions mostly of PM and NO_x but in case of diesel driven vehicles rather than gasoline driven (Keller and Fulper, 2000; Durbin et al., 1998; Beydoun and Guldmann, 2006).

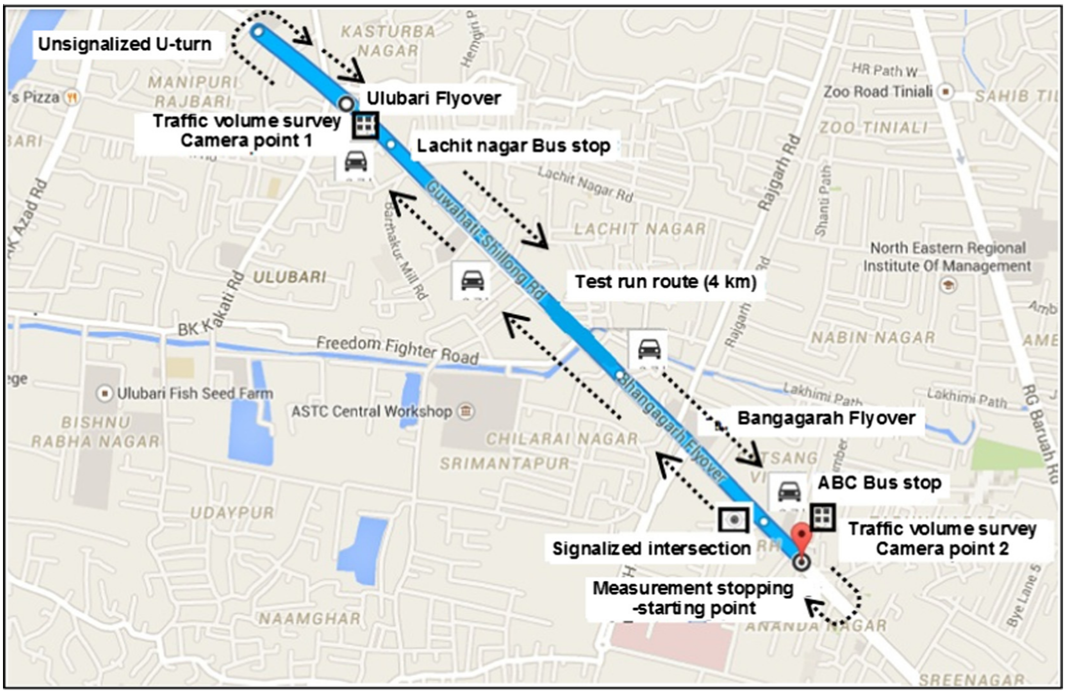

Fig. 1a. Test-run route in the urban center of Guwahati. *Source:* Google map, accessed on 25 January 2015.

Fig. 1b. Section of test-run route at camera point 1.

Tail-pipe emission measurements

Emission measurements were carried out in real-world situations by taking runs of the selected vehicles on the test route along with other vehicles plying on the road at different times of the day especially during PH and OPH. Each test vehicle was run at three different times of the day to capture the real characteristics of the range of speed and acceleration, deceleration of urban traffic. The test vehicles were driven by the owners with the flow of traffic. The basis of the selection of different timings was also to study different traffic-flow patterns. During each time, test run was repeated to produce at least two sets

Table 1
Test vehicle specifications.

Vehicle type	Eon	Omni	Wagon-R	Auto-rickshaw	Auto-rickshaw
Mileage	9200 km	52,000 km	142,000 km	45,000 km	100,000 km
Transmission	4 Speed, manual	5 Speed, manual	5 Speed, manual	4 Forward and one reverse	4 Forward and one reverse
Manufacturer	Hyundai	Maruti suzuki	Maruti suzuki	Bajaj	Bajaj
Weight (kg)	725	785	885	335	335
Max power (bhp)	55 @ 5500 rpm	34.7 @ 5000 rpm	67.06 @ 6200 rpm	7 @ 500 rpm	7 @ 500 rpm
Engine displacement (cc)	814	796	998	145.45	145.45
Bore × stroke (mm^2)	67 × 77	68 × 72	68.5 × 60.4	57 × 57	57 × 57
Cylinder number	3	3	3	1	1
Catalytic convertor	3-Way convertor	3-Way convertor	3-Way convertor	Without	Without

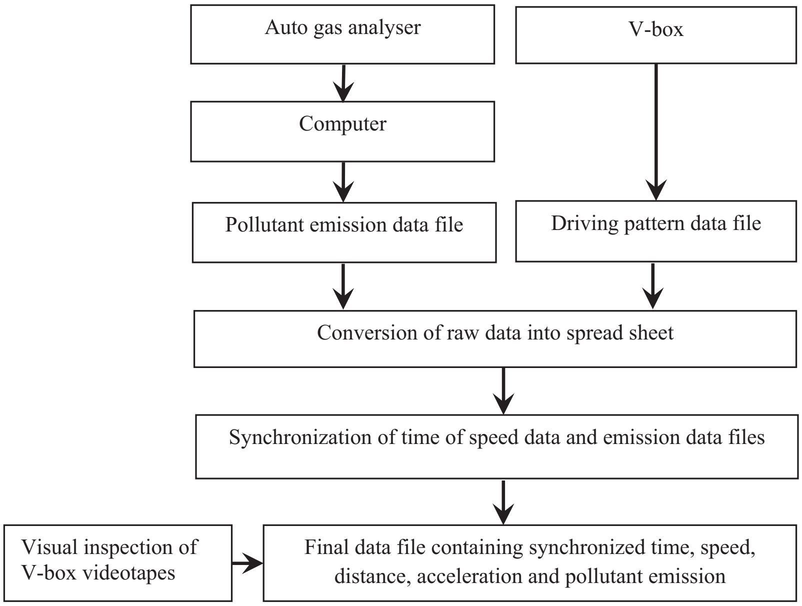

Fig. 2. Data synchronization.

of data. Tests were carried out during 7:00–8:30 am, which is OPH, during 10:30–11:30 am, which covers the morning PH and 4:30–6:30 pm, which covers evening PH.

The measurement system was developed by integrating auto gas analyzer (make: INDUS Scientific Pvt. Ltd., model: PEA205) having a sampling probe and V-box together for measuring instantaneous tailpipe emissions in synchronization with running speed and acceleration and deceleration. The PEA205 has been designed and manufactured as per the international standards (ISO 3430) and national standards as per specifications issued by the Indian Ministry of Transport and Highways in amendment 1 under the document MoRTH/CMVR/TPA-115/116. The auto gas analyzer logs data every second (1 Hz) and V-box records 10 data in 1 s (10 Hz). The auto gas analyzer uses non-dispersive infrared (NDIR) method to detect CO, CO_2, and HC emissions and electrochemical cell to O_2 and NO_x emissions. After installation of the assembly to the vehicle, the auto gas analyzer is calibrated at about every half an hour using ambient air as a reference, referred to as "zeroing". The V-box records vehicle position and video of the test run with its GPS and inbuilt camera. Based on the range of high performance GPS receivers, V-box data logger measures speed, distance, acceleration, braking distance, heading, slip angle, lap times, position, cornering forces with high accuracy.

Data synchronization and analysis

The data recorded by the auto gas analyzer and the V-box were synchronized, and the data obtained for each test vehicle were grouped together. The steps of data synchronization are shown in Fig. 2. The instantaneous mass emission rates of CO, HC, and NO_x of the passenger car and auto-rickshaw, in g/s, were calculated by method described by Saini et al. (2013) as shown in Eq. (1):

$$E_{(g/s)} = ((M_{af} + F_f) * M_Q * Q)/M_{exh} \quad (1)$$

where M_{exh} is the exhaust molar mass, F_f the instantaneous fuel flow rate, M_{af} the mass air flow, $E_{(g/s)}$ the emissions rate, Q the fraction of exhaust gases, and M_Q is the molecular weight of the exhaust gases.

Real-world driving includes a random combination of acceleration, cruise, deceleration, and idle modes. It is important to study emission behaviors during these modes and identify the frequency and intensity of these events and concomitant emissions. Further, it is important to consider the effects of vehicle mileage traveled on emissions different times of day. Emission rates were also expressed in per unit time and per unit distance traveled.

Results and discussion

Impact of speed on emissions

The maximum vehicle speed was observed to be about 45 km/h. The test vehicle during OPH had an average speed of 34 ± 3.7 km/h. The fleet had a large percentage of passenger cars and auto-rickshaws, as shown in Figs. 3 and 4. During critical hours, i.e. PH, the average speed was reduced to 14.6 ± 1.5 km/h. The amount of time passenger cars and auto-rickshaws spent during PH and OPH in different speed intervals along with the total and pollutant wise emissions have been shown in Fig. 3(a–c). The bars indicate the proportions of time the vehicle spent in the corresponding speed range with the overlaid bars showing the total emission rate of CO, HC, and NO_x. The lines indicate the emission rate of CO, HC and NO_x. For over 70% of the time, the passenger car was in the speed lower than 30 km/h, out of which maximum time was in 10–25 km/h, and, therefore, the emission rate during this speed range was also relatively higher, indicating that on urban roads during PH, traffic experiences constant change between congested and interrupted flow conditions. The higher emission rate observed in the speed range of 35–45 km/h might be attributed to a sharp acceleration caused by some events. The emission rate for all the pollutants further increased with increasing mileage as observed in Fig. 3(b) and (c) compared to Fig. 3(a).

Similarly, the auto-rickshaw for about 80% of the time had speed less than 35 km/h in which the most time was in the speed range of 10–35 km/h. The emission rate was also high for the speed range of 10–35 km/h. This indicates that on urban roads during PH, traffic experiences fluctuation between interrupted and free-flow conditions (i.e. 20–35 km/h). It has been observed that for similar mileage travel, auto-rickshaws emitted higher emissions as compared to the passenger cars (Fig. 4a and b). During PH, several parameters such as travel time, traffic density, time in idle mode and congestion period increased. Table 2 shows the time spent by the test vehicles in different flow patterns during both PH and OPH. It was found that during PH, the test vehicles spent 12%, 48%, 32% and 8% of the total time in idle, congested, interrupted and free-flow conditions, respectively, which was observed to be exactly opposite during the OPH. Similarly, traffic density during PH was also much higher than that during the OPH.

Impacts of short-events on emissions

The instantaneous emissions and speeds were analyzed in real-world driving conditions. In the real-world driving, up to 50–60% of the emissions were emitted during sharp peaks lasting for short times. Similar findings have been reported in some studies (Frey et al., 2001; De Haan and Keller, 2000). It was found that the frequency of occurrence of short-lasting peaks depends upon the fluctuation in speed and driving pattern. For this, short-time traces of the test runs of auto-rickshaw and passenger car during PH were analyzed in detailed for examining the effect of sharp accelerating speed on emission levels. Figs. 5 and 6 show only a part of whole time trace, which represents the characteristic run of passenger car and auto-rickshaw, respectively. Figs. 5 and 6 show auto-rickshaw and passenger car instantaneous emissions of CO, HC, NO_x and CO_2 for accelerating and decelerating speeds with sharp drops during PH. It was found that 70% of the time test vehicle had a speed of about 30 km/h with several stop-and-go. It was observed that the frequent stop-and-go produced higher peaks in the emissions of CO, HC, and NO_x. The stop-and-go pattern involves frequent gearshift and high-power interval (Elmi and Al Rifai, 2012) and the main causes of higher emission and, thus, increases the amount of emissions during PH. A sharp rise in emission rates was observed when the test vehicles encountered a sharp acceleration as well as deceleration lasting for 5–7 s. The highest peak in the pollutant emissions was observed during deceleration at around 121 s (Fig. 6). Similar observations are made by Zhang et al. (2011). These pollutants are emitted at higher rates during sharp peaks. These peaks occur for a small amount of time during the trip. Emission rates start increasing the same time when acceleration and deceleration starts increasing and reach highest levels and stay at that level as long as vehicle stays in that driving mode. During sharp decelerations fuel injection cuts off, which leads to the cylinder misfire producing higher emission puffs (Fig. 6) (Goodwin and Ross, 1996; An et al., 1997). It has been further observed that CO_2 emissions follow the speed profile and sharp and continuous drops in speed also reduced the emissions.

The results of this analysis for both passenger cars and auto-rickshaws were indicative of the high emissions during sharp and continuous acceleration, irrespective of the low or high vehicle speed.

Impacts of traffic-flow patterns on emissions

Emission factors (EF) vary with operation characteristics, vehicle age, vehicle category and model and with different control measures. Table 3 shows the EF reported in several recent studies for different traffic-flow conditions, modal years, and

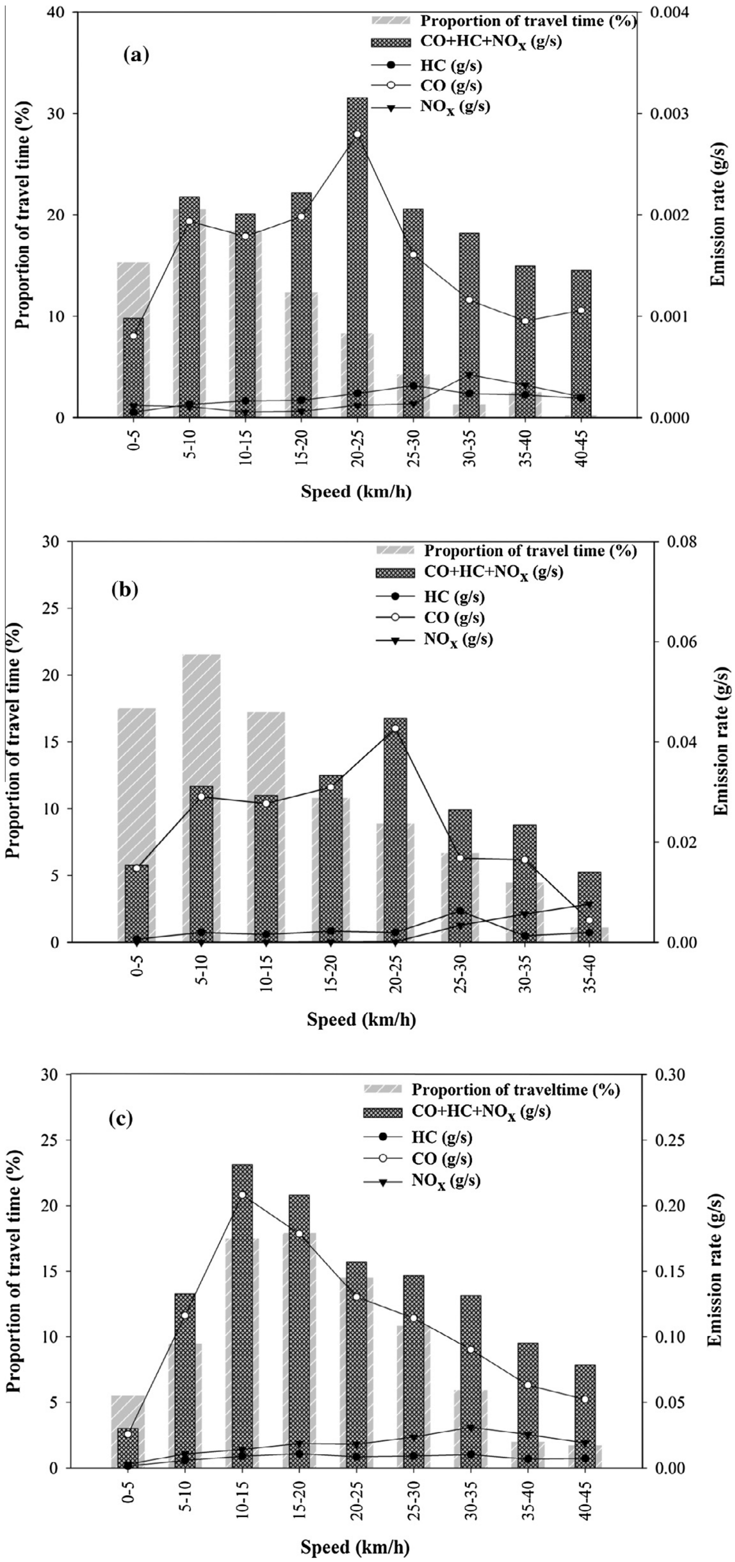

Fig. 3. The emission rate and proportion of travel time distributions for different speed classes in three different mileage range passenger cars; (a) 9200 km, (b) 52,000 km, and (c) 142,000 km.

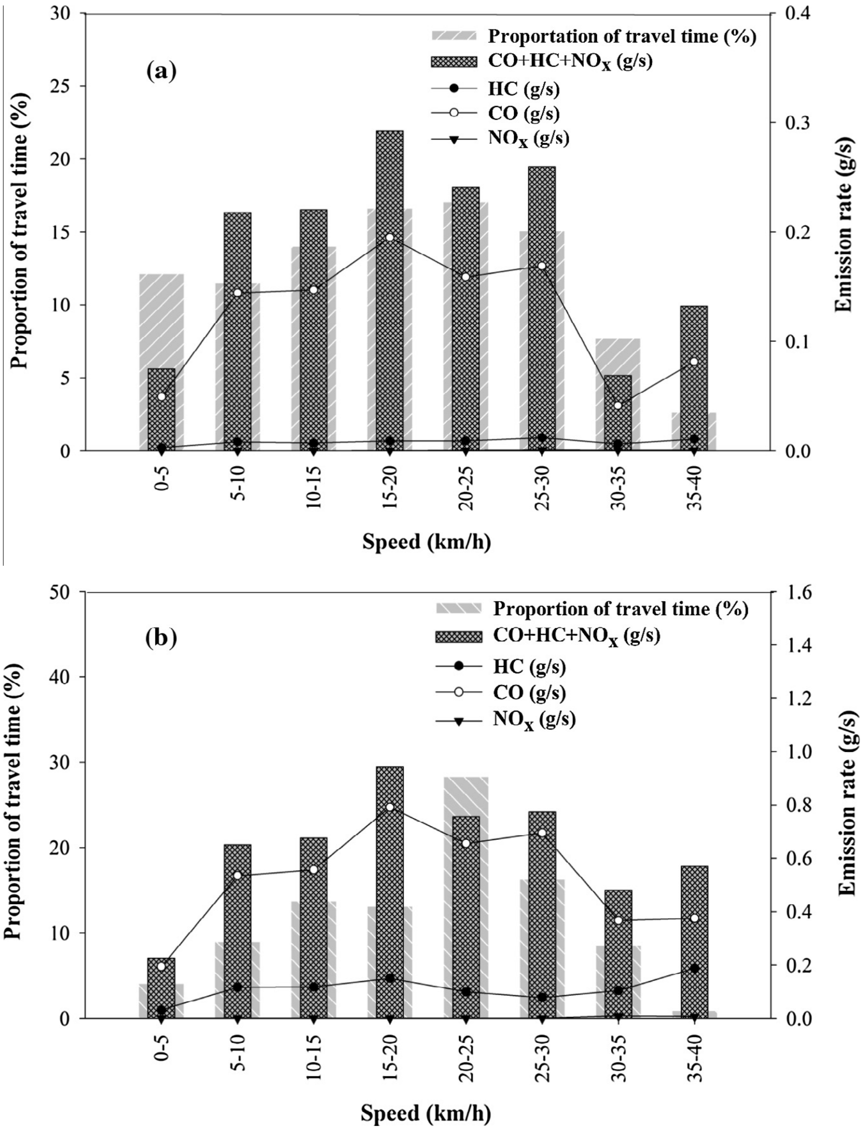

Fig. 4. The emission rate and proportion of travel time distributions for different speed classes in two different mileage range auto-rickshaw; (a) 45,000 km and (b) 100,000 km.

Table 2
Traffic flow characteristics during OPH and PH.

Characteristics	OPH	PH
Distance (km)	3.8	3.8
Time (s)	477 ± 43	904 ± 93.3
Average speed (km/h)	34 ± 3.7	14.6 ± 1.5
Congestion period (%)	11.3 ± 4.4	47.8 ± 4.4
Interrupted period (%)	15.3 ± 2	31.6 ± 3.7
Free flow period (%)	62.9 ± 1.5	8.25 ± 2
Idle period (%)	5.9 ± 1	12.25 ± 2.8
Density[a] (veh/km)	31 ± 4	373 ± 7

[a] Travel time of each vehicle category was determined for 5 min difference during PH and OPH from the videotapes over 100 m stretch, which gives the speed of vehicle. Further speeds and traffic flow rate (veh/h) were used to calculate roadway density.

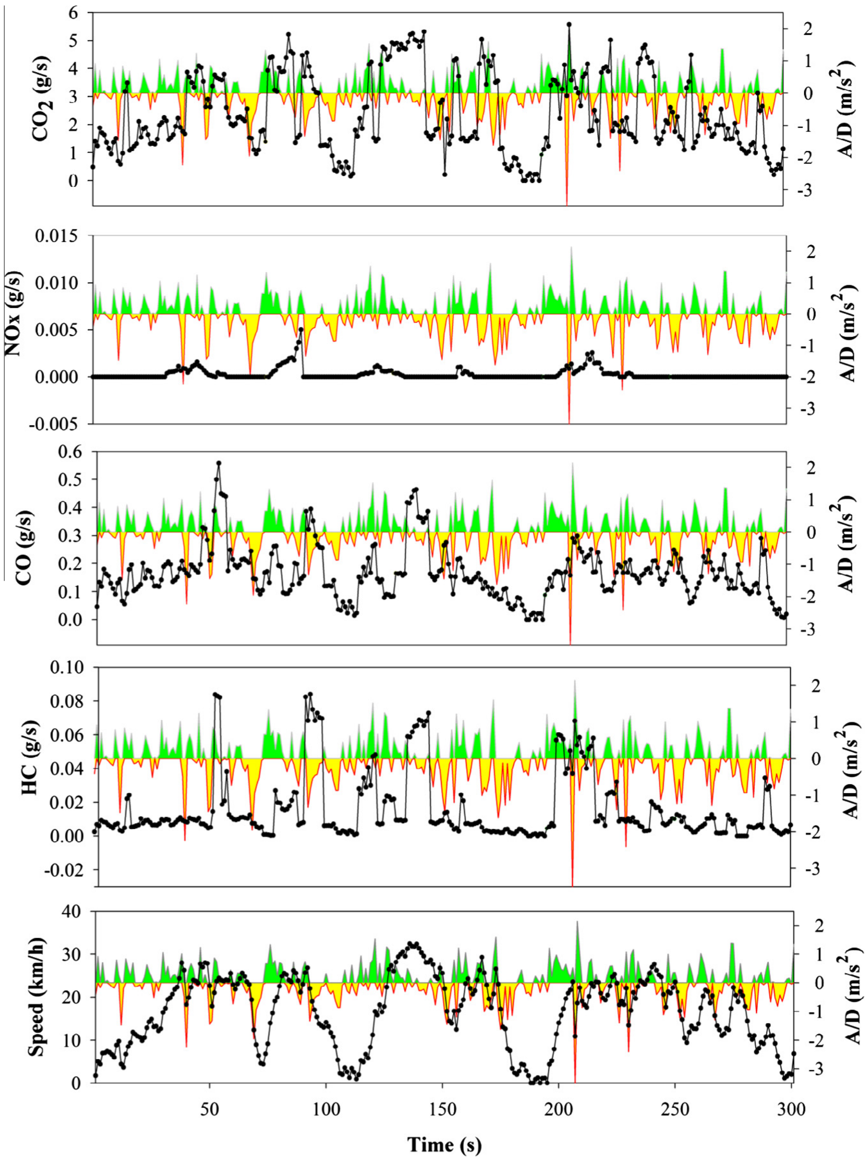

Fig. 5. The instantaneous emission of CO, HC, NO_x and CO_2 with moderately fluctuating speed in auto-rickshaw during PH.

different vehicle classes and for different mileages. EF differ considerably from study to study, which may be attributed to the differences in traffic density, vehicle mix, driving patterns land-use patterns, road infrastructure, and traffic management.

Table 4 lists emission rates (in g/km) for the two vehicle classes and three traffic conditions. The percentage share of CO_2 in the total emissions in all traffic-flow conditions was about 98% with 2% shared by the remaining pollutants. For passenger car, the EF of CO and HC were found to be about 3–4 times higher during congested flow (at average speed 8.5 ± 4 km/h) and 1.5–2.5 times higher during interrupted flow condition (at average speed 21 ± 4 km/h) as compared to the free-flow condition (at average speed 33 ± 4 km/h). However, the EF of NO_x was about 1.5–2.5 times higher during free-flow condition as compared to the congested flow. For auto-rickshaw, the EF of CO and HC were found to be about 2–8 times higher during congested flow and 2–5 times during interrupted flow as compared to free-flow condition and NO_x was 2–5 times higher during free-flow as compared to the congested flow.

Table 5 shows the EF for different mileage passenger cars and auto-rickshaws. For passenger car, for example, as mileage increased from 9200 to 52,000 km and to 142,000 km the EF of CO and HC also increased considerably, e.g. for mileages from 9200 to 52,000 km led to 6–12 times increase in the EF of CO, HC and NO_x and with the further increase in mileage to 142,000 km, the EF increased about 40–52 times from the EF observed for the vehicles with mileage of 9200 km. During PH, the EF of CO and HC were 2–4 times higher as compared to OPH and of NO_x was about 2 times higher during OPH.

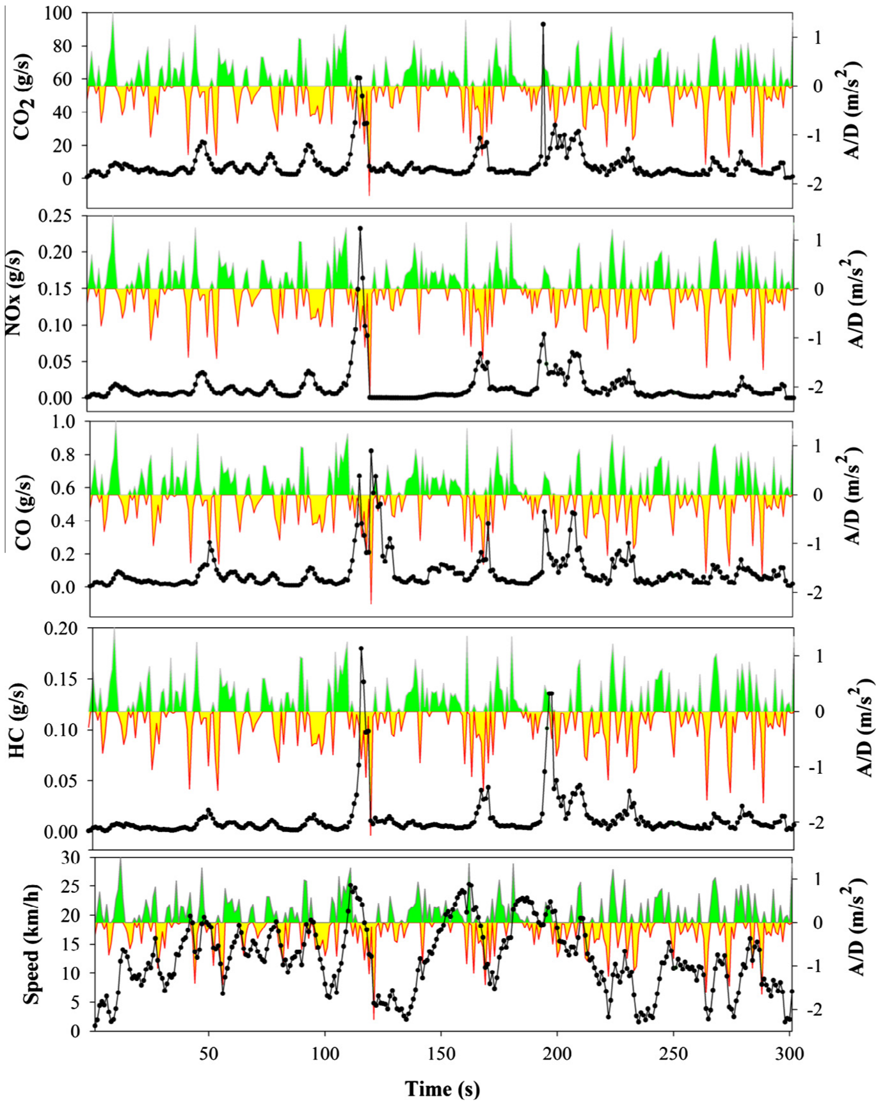

Fig. 6. The instantaneous emission of CO, HC, NO_x and CO_2 with moderately fluctuating speed in passenger car during PH.

For auto-rickshaw as mileage increased from 45,000 to 100,000 km, the EF of CO, HC increased about 3–8 times and of NO_x increased about 18 times. During PH, EF of CO and HC was found to be about 4–7 times higher from OPH and of NO_x was about 2 times higher in OPH.

Discussion

Urban traffic-flow pattern in real-world driving is unpredictable, especially during peak hours. Most times, it changes between interrupted and congested conditions. This impacts emissions considerably, which are released at higher rate during these flow conditions and also during the transition. Passenger cars and auto-rickshaws both have different behaviors at the same flow speed. As demonstrated in this study, a passenger car and an auto-rickshaw on urban roads spends most time in the speed of interval 10 (±3.8)–25 (±4.3) km/h and 15 (±3.3)–35 (±3.5) km/h, respectively. Auto-rickshaws being small in size have a higher average speed as compared to passenger cars and, therefore, most time travel in the interrupted flow condition with aggressive driving with sudden break and sharp acceleration, which make them more emission intensive than passenger cars.

The impacts of sharp acceleration and frequent stop-and-go patterns were investigated in the short-event analysis. The passenger car and auto-rickshaw both show the highest emissions of CO, HC and NO_x during sharp and continuously accelerating and decelerating speeds. Due to sharp acceleration or deceleration, more fuel is injected to engine cylinder, which increases load on the engine leading to elevated levels of CO and HC (Wenzel et al., 2001). Whereas, sharp decelerations

Table 3
EF variation with different variable from recent studies.

References	Pollutant	EF (g/km)	
Yao et al. (2007) (car)		*Freeway*	*Arterial*
For 14,800 mileage	CO	2.39	3.88
	HC	0.15	0.25
	NO_x	0.08	0.11
For >81,000 mileage	CO	3.66	5.92
	HC	0.11	0.18
	NO_x	0.40	0.58
Wang et al. (2014)		*Model ⩽ 2000*	*Model > 2000*
	CO	14.6 ± 22.9	0.23 ± 0.29
	HC	3.19 ± 5.04	0.02 ± 0.02
	NO_x	2.57 ± 2.12	0.1 ± 0.13
Sahu et al. (2014) (passenger car, PC; and three wheeler, 3W)		*2001–2005*	*2006–2010*
	CO	1.37 (3W), 1.3 (PC)	1.37 (3W), 0.84 (PC)
	NO_x	0.2 (3W), 0.2 (PC)	0.2 (3W), 0.09 (PC)
Kristensson et al. (2004) (all type vehicles, tunnel study)	CO	6.2 ± 0.2	
	NO_x	1.3 ± 0.12	
Kohler et al. (2005) (all type vehicles, tunnel study)	CO	2.62 ± 0.13	
	NO_x	0.68 ± 0.12	
Steinemann and Zumsteg (2003) (LDV)	CO	1.9–4.4	
	NO_x	0.6–1.8	
Hwa et al. (2002) (all type vehicles, tunnel study)	CO	3.46 ± 0.26	
	NO_x	0.9 ± 0.18	
Fu et al. (2001) (car)	CO	43.2	
	HC	4.3	
	NO_x	1.6	
Mashelkar et al. (2002) (auto-rickshaw)	CO	4.3	
	HC	2.05	
	NO_x	0.11	

Table 4
Emissions during different traffic flow patterns and traffic speed.

Vehicle type and mileage (km)	Traffic condition	No. of trips	Speed (km/h)	CO (g/km)	HC (g/km)	NO_x (g/km)
Passenger car						
(1) 9200 km	Congested flow	4	9.36 ± 3.8	0.78 ± 0.69	0.07 ± 0.05	0.07 ± 0.08
	Interrupted flow	4	21.71 ± 4.3	0.34 ± 0.27	0.04 ± 0.01	0.04 ± 0.05
	Free flow	4	36.39 ± 4.5	0.18 ± 0.15	0.02 ± 0.02	0.05 ± 0.036
(2) 52,000 km	Congested flow	4	7.38 ± 4	11.91 ± 8.2	0.69 ± 0.43	0.02 ± 0.03
	Interrupted flow	4	21.65 ± 4.2	6.26 ± 5.06	0.37 ± 0.24	0.02 ± 0.02
	Free flow	4	33.79 ± 3.4	1.18 ± 0.09	0.24 ± 0.16	0.05 ± 0.03
(3) 142,000 km	Congested flow	4	8.7 ± 3.9	26.76 ± 23.63	3.04 ± 2.4	1.67 ± 1.15
	Interrupted flow	4	20.9 ± 3.5	17.25 ± 11.04	1.89 ± 1.37	1.47 ± 1.32
	Free flow	4	32.3 ± 1.7	7.61 ± 5.4	0.82 ± 0.61	2.62 ± 1.57
Auto-rickshaw						
(1) 45,000 km	Congested flow	4	8.5 ± 3.9	50.62 ± 32.9	2.72 ± 1.75	0.02 ± 0.03
	Interrupted flow	4	21.2 ± 4.3	29.64 ± 10.8	1.65 ± 0.6	0.035 ± 0.02
	Free flow	4	34.13 ± 4.5	6.81 ± 5.2	1.02 ± 0.8	0.05 ± 0.03
(2) 100,000 km	Congested flow	4	9.6 ± 3.9	76.94 ± 65.7	17.67 ± 13.4	0.17 ± 0.11
	Interrupted flow	4	20.5 ± 3.5	43.17 ± 34.2	7.85 ± 5.2	0.16 ± 0.07
	Free flow	4	33.9 ± 4.0	23.07 ± 18.5	8.03 ± 2.5	0.76 ± 0.44

cause cylinder misfire, which produces high emission puffs. Several studies have demonstrated that sharp acceleration, low speed and rate of stop-and-go condition are the root cause of higher emission (Cheng-Wei, 2013; Manzie et al., 2007; Nie and Li, 2013). Sharp acceleration or deceleration at a high speed consume more fuel increasing more HC, CO but the increase in NO_x is negligible, so the rate of increase or decrease of all the pollutants is not same.

The EF expressed in g/km indicates that emissions of both test vehicles increase about 2–7 times during the PH (both morning and evening) over the emissions during OPH. The auto-rickshaws had higher EF of CO and HC over passenger cars, almost 7 and 4 times, respectively, but the EF of NO_x was 2 times higher in passenger cars. Vehicle emission rate varies considerably with speed and acceleration (Chen et al., 2007), and with engine type and power/load conditions (Faiz et al., 1996).

Table 5
Emissions during OPH and PH.

Vehicle category	Traffic flow condition	Travel time (s)	Distance (km)	CO (g/km)	HC (g/km)	NO_x (g/km)
Passenger car						
(1) 9200 km	FF	450.0	3.8	0.18 ± 0.15	0.02 ± 0.02	0.05 ± 0.08
	MP	1124.5	3.8	0.59 ± 0.4	0.046 ± 0.04	0.03 ± 0.01
	EP	737.0	3.8	0.50 ± 0.43	0.051 ± 0.04	0.05 ± 0.04
(2) 52,000 km	FF	425.6	3.9	1.02 ± 0.09	0.24 ± 0.16	0.11 ± 0.03
	MP	1154.0	3.9	8.79 ± 6.71	0.52 ± 0.41	0.05 ± 0.02
	EP	–		–	–	–
(3) 142,000 km	FF	503.0	3.7	7.61 ± 5.4	0.82 ± 0.61	2.62 ± 1.57
	MP	815.0	3.8	34.13 ± 26.1	1.91 ± 1.48	1.41 ± 1.55
	EP	939.0	3.8	20.82 ± 16.2	2.32 ± 1.8	1.55 ± 1.1
Auto-rickshaw						
(1) 45,000 km	FF	510.0	3.9	6.81 ± 5.2	1.02 ± 0.08	0.05 ± 0.03
	MP	720.0	3.7	35.39 ± 14.8	1.94 ± 1.4	0.04 ± 0.03
	EP	787.0	3.8	57.59 ± 22.1	2.84 ± 1.3	0.03 ± 0.02
(2) 100,000 km	FF	504.0	3.7	23.07 ± 18.5	8.03 ± 2.5	0.88 ± 0.44
	MP	798.0	3.8	55.26 ± 22.3	11.37 ± 5.8	0.51 ± 0.48
	EP	693.0	3.8	120.70 ± 47.2	19.82 ± 11.8	0.54 ± 0.52

Note: FF – free flow, MP – morning peak time, and EP – evening peak time.

Auto-rickshaws use 2-stroke engines without catalytic convertor, and therefore produce higher emissions of CO and HC than passenger cars.

This study, therefore, demonstrated that mitigations targeted to reduce emissions in urban areas need consideration of traffic-flow patterns. The interrupted flow condition and the time spent in this condition can be reduced by a suitable traffic flow management strategy. If interruptions are reduced, congestion would be less likely on urban roads.

Conclusion

Traffic congestion occurs during both peak and off-peak hours. Traffic spends more time in congestion during peak hours than it spends during off-peak hours and hence emissions rise nearly double during peak hours. Passenger cars and auto-rickshaws both have different flow characteristics at the same speed and emissions of CO and HC are high in auto-rickshaws and of NO_x in passenger cars. Short-events like frequent gearshift and frequent stop-and-go occurring during interruptions and congestion are the main causes of higher emissions on urban roads since they lead to sharp increase or decrease in acceleration and deceleration. Emissions continue increasing as long as the vehicle is in acceleration or deceleration. Therefore, the number of the occurrences of sharp acceleration and deceleration and the time spent in each mode determines the amount of emission significantly. Traffic flow patterns when change from free to interrupted to congested, emission load of CO and HC emissions also increases in that order.

References

An, F., Barth, M., Ross, M., Norbeck, J., 1997. The development of a comprehensive modal emissions model: operating under hot-stabilized conditions. Transport. Res. Rec. 1587, 52–62.

Bachman, W.H., 1998. A GIS-based modal model of automobile exhaust emissions. Final Report, EPA Cooperative Agreement CR823020. Prepared for: US Environmental Protection Agency, Office of Research and Development, Washington, DC, 20460.

Beydoun, M., Guldmann, J.M., 2006. Vehicle characteristics and emissions: logit and regression analyses of I/M data from Massachusetts, Maryland, and Illinois. Transport. Res. Part D 11, 59–76.

Chen, C., Huang, C., Jing, Q., Wang, H., Pan, H., Li, L., Schipper, L., 2007. On-road emission characteristics of heavy-duty diesel vehicles in Shanghai. Atmos. Environ. 41 (26), 5334–5344.

Cheng-Wei, S.U., 2013. Characteristics of emissions and vehicular operations of buses in Taipei's exclusive bus lanes. In: Proceedings of the Eastern Asia Society for Transportation Studies, vol. 9.

Central Pollution Control Board. Air Quality Trends and Action Plan for Control of Air Pollution from Seventeen Cities. Series: NAAQMS/29/2006-07, September 2006.

De Haan, P., Keller, M., 2000. Emission factors for passenger cars: application of instantaneous emission modeling. Atmos. Environ. 34 (27), 4629–4638.

De Vlieger, I., De Keukeleere, D., Kretzschmar, J., 2000. Environmental effects of driving behaviour and congestion related to passenger cars. Atmos. Environ. 34 (27), 4649–4655.

Durbin, T.D., Truex, T.J., Norbeck, J.M., 1998. Particulate Measurements and Emissions Characterization of Alternative Fuel Vehicle Exhaust. Center for Environmental Research and Technology, College of Engineering, University of California, Riverside.

Elmi, A., Al Rifai, N., 2012. Pollutant emissions from passenger cars in traffic congestion situation in the State of Kuwait: options and challenges. Clean Technol. Environ. Policy 14 (4), 619–624.

Faiz, A., Weaver, C.S., Walsh, M.P., 1996. Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions. World Bank Publications.

Frey, H.C., Rouphail, N.M., Unal, A., Colyar, J.D., 2001. Measurement of on-road tailpipe CO, NO, and hydrocarbon emissions using a portable instrument. In: Paper Presented at the Proceedings, Annual Meeting of the Air & Waste Management Association.

Frey, H.C., Unal, A., Rouphail, N.M., Colyar, J.D., 2003. On-road measurement of vehicle tailpipe emissions using a portable instrument. J. Air Waste Manage. Assoc. 53 (8), 992–1002.

Fu, L., Hao, J., He, D., He, K., Li, P., 2001. Assessment of vehicular pollution in China. J. Air Waste Manage. Assoc. 51 (5), 658–668.
Gakenheimer, R., 2002. Planning Transportation and Land Use for Cities in India. Massachusetts Institute of Technology, Cambridge, MA.
Gokhale, S., 2012. Impacts of traffic-flows on vehicular-exhaust emissions at traffic junctions. Transport. Res. Part D: Transp. Environ. 17, 21–27.
Goodwin, R.W., Ross, M., 1996. Off-cycle Exhaust Emissions from Modern Passenger Cars with Properly-functioning Emissions Controls. Society of Automotive Engines, Technical Paper Number 960064.
Guensler, R.L., 1993. Vehicle Emission Rates and Average Vehicle Operating Speeds.
Guerrieri, M., Corriere, F., Casto, B.L., Rizzo, G., 2015. A model for evaluating the environmental and functional benefits of "innovative" roundabouts. Transport. Res. Part D: Transp. Environ. 39, 1–16.
Hwa, M.Y., Hsieh, Ch.Ch., Wu, T.Ch., Chang, L.F.W., 2002. Real-world vehicle emissions and VOCs profile in the Taipei Tunnel located at Taiwan Taipei area. Atmos. Environ. 36, 1993–2002.
Keller, C., Fulper, A., 2000. A study of in-use emissions on light heavy-duty diesel vehicles at different payloads using a chassis dynamometer. In: Tenth Annual Coordinating Research Council On-Road Vehicle Emissions Workshop, San Diego.
Kohler, M., Corsmeier, U., Vogt, U., Vogel, B., 2005. Estimation of gaseous real-world traffic emissions downstream a motorway. Atmos. Environ. 39 (31), 5665–5684.
Kristensson, A., Johansson, Ch., Westerholm, R., Swietlicki, E., Gidhagen, L., Wideqvist, U., Vesely, V., 2004. Real world traffic emission factors of gases and particles measured in a road tunnel in Stockholm, Sweden. Atmos. Environ. 38, 657–673.
Li, J., 2011. Decoupling urban transport from GHG emissions in Indian cities—a critical review and perspectives. Energy Policy 39 (6), 3503–3514.
Li, X., Li, G., Pang, S.S., Yang, X., Tian, J., 2004. Signal timing of intersections using integrated optimization of traffic quality, emissions and fuel consumption: a note. Transport. Res. Part D: Transp. Environ. 9 (5), 401–407.
Manzie, C., Watson, H., Halgamuge, S., 2007. Fuel economy improvements for urban driving: hybrid vs. intelligent vehicles. Transport. Res. Part C: Emerg. Technol. 15 (1), 1–16.
Mashelkar, R.A., Biswas, D.K., Krishnan, N.R., Mathur, O.P., Natarajan, R., Niyati, K.P., Shukla, P.R., Singh, D.V., Singhal, S., 2002. Report of the expert committee on auto fuel policy. Ministry of Petroleum and Natural Gas, Government of India, New Delhi.
Nie, Y.M., Li, Q., 2013. An eco-routing model considering microscopic vehicle operating conditions. Transport. Res. Part B: Methodol. 55, 154–170.
Pandian, S., Gokhale, S., Ghoshal, A.K., 2009. Evaluating effects of traffic and vehicle characteristics on vehicular emissions near traffic intersections. Transport. Res. Part D: Transp. Environ. 14 (3), 180–196.
Ramachandra, T., 2009. Emissions from India's transport sector: state wise synthesis. Atmos. Environ. 43 (34), 5510–5517.
Reynolds, C.C., Kandlikar, M., Badami, M.G., 2011. Determinants of PM and GHG emissions from natural gas-fueled auto-rickshaws in Delhi. Transport. Res. Part D: Transp. Environ. 16 (2), 160–165.
Robertson, H.D., 1994. Queuing studies. In: Robertson, H.D., Hummer, J.E., Nelson, D.C. (Eds.), Manual of Transportation Engineering Studies, Washington, DC, pp. 347–358. <http://trid.trb.org/view/759186> (accessed on October 24, 2015).
Sahu, S.K., Beig, G., Parkhi, N., 2014. Critical emissions from the largest on-road transport network in South Asia. Aerosol Air Qual. Res. 14 (1), 135–144.
Saini, B., Verma, R., Himanshu, S., Gupta, S., 2013. Analysis of exhaust emissions from gasoline powered vehicles in a sub-urban Indian town. Int. Res. J. Environ. Sci. 2 (1), 37–42.
Shukla, A., Alam, M., 2010. Assessment of real world on-road vehicle emissions under dynamic urban traffic conditions in Delhi. Int. J. Urban Sci. 14 (2), 207–220.
Singh, S.K., 2006. Future mobility in India: implications for energy demand and CO_2 emission. Transp. Policy 13 (5), 398–412.
Steinemann, U., Zumsteg, F., 2003. Verkehrs-und Schadstoffmessungen 2002 im Gubristtunnel. Ostluft, Amt für Abfall, Wasser, Energie und Luft des Kantons Zürich (AWEL), Auftragsnummer US 89-16.
Tollazzi, T., Tesoriere, G., Guerrieri, M., Campisi, T., 2015. Environmental, functional and economic criteria for comparing "target roundabouts" with one-or two-level roundabout intersections. Transport. Res. Part D: Transp. Environ. 34, 330–344.
Wang, Z., Wu, Y., Zhou, Y., Li, Z., Wang, Y., Zhang, S., Hao, J., 2014. Real-world emissions of gasoline passenger cars in Macao and their correlation with driving conditions. Int. J. Environ. Sci. Technol. 11 (4), 1135–1146.
Wenzel, T., Singer, B.C., Slott, R., 2001. Some issues in the statistical analysis of vehicle emissions. Statistical Analysis and Modeling of Automotive Emissions, vol. 1. MoRTH/CMVR/TPA-115/116. <https://www.araiindia.com/CMVR_TAP_Documents/Amendment 1 to Tap Issue 4_1.pdf> (July 10, 2015).
Yao, Z., Wang, Q., He, K., Huo, H., Ma, Y., Zhang, Q., 2007. Characteristics of real-world vehicular emissions in Chinese cities. J. Air Waste Manage. Assoc. 57 (11), 1379–1386.
Zhai, H., Frey, H.C., Rouphail, N.M., 2008. A vehicle-specific power approach to speed-and facility-specific emissions estimates for diesel transit buses. Environ. Sci. Technol. 42 (21), 7985–7991.
Zhang, K., Batterman, S., Dion, F., 2011. Vehicle emissions in congestion: comparison of work zone, rush hour and free-flow conditions. Atmos. Environ. 45 (11), 1929–1939.