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Analysis of driving characteristics and estimation of pollutant emissions from intra-city buses

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Abstract

Intra-city buses provide essential transportation and mobility services in cities. However, most of the buses in Indian cities run on diesel fuel causing significant emissions and air quality issues. This study aims to quantify the emissions from the buses during peak and off-peak periods using second-by-second activity data collected using global positioning system (GPS) receivers. Four-bus routes plying within the city of Chennai in India was selected and second-by-second speed and acceleration was used to determine the operating mode of the bus. Corresponding emissions were estimated using vehicle specific power (VSP). Results show that the average speed of the bus during peak and off-peak periods were 17.8 kmph and 21.5 kmph, respectively; the corresponding percentages of time idling were 27% and 22%. Further, the percentage increase in total emissions of CO_2, CO, HC and NO_x from the bus during peak periods with respect to off-peak periods was 17%, 16%, 37% and 21%, respectively. This study provides useful insights regarding the operating and emission characteristics of buses that will be valuable to policy makers in improving their service and efficiency.

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Keywords: Buses; Emissions; Driving characteristics; Vehicle specific power.

1. Introduction

Buses play a vital role in satisfying the transportation and mobility needs of the inhabitants on any city. Almost all the cities in the world have a well-developed bus transportation system providing connectivity to different parts of the city. Many cities also have other modes of transport such as metro-rail and mono-rail. Despite bus transport

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experiencing stiff competition from rail-based transport, buses continue to serve as feeder to the rail services as they provide last mile connectivity to the commuters. In addition, the operation of buses does not require any additional infrastructure to be set up and can be easily altered to different time schedules and routes. This is crucial with regard to developing countries facing shortage of funds and resources. Thus, buses play an indispensable role in meeting the transportation needs of the residents of a city.

Many cities in India have well developed bus transportation system which are operated and managed by the respective transport corporations. In Delhi, the Delhi Transport Corporation (DTC) operates about 3,106 compressed natural gas (CNG) buses on 773 routes (Source: dtc.nic.in). In Bangalore, the Bangalore Metropolitan Transport Corporation (BMTC) owns 6,122 buses, carrying 4.8 million passengers per day. Overall, bus transport has a share of 30% of all trips. In Ahmedabad, 900 buses carry about 900,000 passengers a day accounting for a share of 8% of all trips. Besides, Janmarg, India's first fully-fledged bus rapid transit system (BRTS) is operational in Ahmedabad.

The study area of Chennai also has well-developed bus transport. Intra-city buses in Chennai are owned and operated by the Metropolitan Transport Corporation (MTC), an undertaking of the Government of Tamil Nadu. Currently, MTC has a fleet size of 4,010 buses with an average age of 6.83 years. Around 800 bus routes of different service types ply on a daily basis. Daily average kilometers travelled by a bus is approximately 295 km (Source: mtcbus.org). However, buses experience severe overcrowding during peak-hours with more than 70 passengers travelling in the bus at one time. This leads to inconvenience to passengers thereby causing drop in bus ridership and promotes the use of personal vehicles for work trips.

Driving characteristics of a vehicle provide useful information regarding the operation of the vehicle which can be used for evaluating efficiency. With the widespread availability of Global Positioning System (GPS) devices, recording accurate second-by-second location and speed data of any vehicle has become relatively easy. Further, the second-by-second vehicle activity (speed and acceleration) data can be used for estimating emissions directly or by developing a driving cycle from the data.

Thus, the objectives of this study are to examine the different driving characteristics of intra-city buses during peak and off-peak periods and to estimate the resulting emissions. The results of this study would be useful to policy makers in understanding the driving characteristics of intra-city buses and in deciding the impact of these buses on air quality of the city.

2. Literature review

Many studies have used second-by-second GPS data of vehicles to determine the driving characteristics and in developing real-world driving cycles for emission testing. Hung et al. (2005) collected speed-time data in peak and non-peak periods on both weekdays and weekends in three cities of Pearl River Delta (Hong Kong, Macao and Zhuhai), China. Car chasing technique was used to collect data with the experimental car equipped with infrared tachometer, microwave speed sensor and GPS receiver. The study found all the cities having percentage of acceleration and deceleration above 30% in all periods. Wang et al. (2008) analyzed driving characteristics for eleven cities in China, covering different sizes and locations. Speed-time data was collected in each city on freeways, arterials, and residential roads during peak and off-peak periods. The range of average speed during off-peak period was between 23 and 41 kmph; whereas during peak-hour the range of average speed was between 16 and 31 km/h. The study found that city size, local road infrastructure, and driving behavior lead to significant differences in vehicle driving patterns among the cities. Proportion of idling in Beijing was 16% and 29% during off-peak and peak hours, respectively whereas the corresponding values in Shanghai were 19% and 38%. In another study in Beijing, Lai et al. (2013) analyzed driving characteristics of transit buses using eight assessment parameters including average speed, average acceleration, average deceleration, average dwell time, idling proportion, acceleration proportion, cruising proportion, and deceleration proportion. Three different bus lines, namely BRT, express and regular, were chosen for the study. The average speeds of BRT, express, and regular lines were 20.71, 25.5, and 15.16 km/h, respectively. The proportion of time spent in acceleration and deceleration were 59.08%, 69.73%, and 56.76%, respectively.

In India, Kamble et al. (2009) developed driving cycles using speed-time data collected using chase-car technique in Pune. The study found that average speed on the city roads ranges between 15 km/h and 35 km/h. The target parameters used to determine the driving cycle were percentage acceleration (14.58), percentage deceleration

(12.23), percentage cruise (54.63), and percentage idle (18.61). Nesamani and Subramanian (2011) used GPS to study the driving characteristics of intra-city buses in Chennai, India. The study found that a higher percentage of total time was spent in idle mode in all types of roads and during both peak and off-peak periods. The average speed of most of the trips were below 30 km/h.

The driving characteristics determined from the instantaneous speed has been widely used to determine vehicle specific power (VSP), which has been found to be highly correlated with emissions. VSP is defined as the power required per unit mass of the vehicle and is a function of speed, acceleration, and road grade. Zhai et al. (2008) developed a VSP based approach to estimate emissions for diesel transit buses. The VSP values were classified into eight modes and each mode was assigned an average emissions rate based on the in-use testing of 12 buses using portable emission measurement systems (PEMS). However, the tested buses were unloaded. Alam and Hatzopoulou (2014) used output from traffic microsimulation model to determine VSP and operating mode of the bus in Montreal, Canada. Zhang et al. (2014) tested seventy-five transit buses of different fuel types in Beijing to determine real-world fuel consumption and CO_2 emissions. The driving characteristics data collected using GPS was used to determine operating modes of the vehicle. Each operating mode was based on vehicle speed and VSP. Yu et al. (2016) used VSP to quantify fuel consumption and emissions from diesel bus in Nanjing, China. The real-world emissions were measured using PEMS and divided into 31 bins based on vehicle speed and VSP.

From the review of existing literature, it is evident that driving characteristics determined using second-by-second GPS data provide accurate input to estimate emissions. Further, it is seen that VSP based approach to quantify emissions has been widely adopted. However, the only study in this area in India is by Nesamani and Subramanian (2011), which analyzed driving characteristics of buses, but did not estimate the corresponding emissions.

3. Data collection

The second-by-second data from four bus routes were collected on a weekday in the month of August, 2016 using hand-held GPS units. The data collected included date, time, latitude, longitude, altitude, and instantaneous speed. From the second-by-second speed, acceleration and deceleration were determined. The data consisted of twenty-five trips of the bus from origin to destination for all the four routes during peak (10 trips) and off-peak periods (15 trips). For each trip, the start time, end time, and journey time were recorded. The route length and scheduled journey time of the routes are shown in Table 1.

Table 1. Details of the study routes.

Route number	Route length (km)	Journey time (min.)
R1	19.5	65
R2	24.3	75
R3	36.5	100
R4	40	100

4. Analysis of driving characteristics

From the literature review, the following driving parameters were identified for characterization of driving conditions:

- Average speed (V_1) – Average of the entire journey speed including idling
- Average running speed (V_2) – Average speed excluding idling time
- Maximum speed (V_{max}) – Maximum speed observed during the trip
- Average acceleration (A) – Average acceleration of all acceleration phases
- Average deceleration (D) – Average deceleration of all deceleration phases
- Maximum acceleration (A_{max}) – Maximum acceleration of entire trips
- Maximum deceleration (D_{max}) – Maximum deceleration of entire trips

- Percentage of time spent in idle mode (P_i) – Both speed and acceleration equals zero
- Percentage of time spent in acceleration mode (P_a) – Speed greater than 5 kmph and acceleration greater than 0.1 m/s^2
- Percentage of time spent in deceleration mode (P_d) – Speed greater than 5 kmph and deceleration greater than 0.1 m/s^2
- Percentage of time spent in creeping mode (P_{cr}) – Speed less than 5 kmph excluding idling
- Percentage of time spent in cruise mode (P_c) – Speed greater than 5 kmph and acceleration between -0.1 and 0.1 m/s^2.
- Number of stops per km (Stops/km) – Total route length divided by the total number of stops including stops due to signalized intersections and congestion

Figure 1 compares the average speed during peak and off-peak periods for the four bus routes. It is seen that average speed during peak period is below 20 kmph for three routes with significant difference relative to off-peak hour. Average speed is almost the same during peak and off-peak periods for route 1. Moreover, average speed during off-peak is also less than 25 kmph for three bus routes which is significantly low. Further, considerable difference is seen between average speeds on different routes. Figure 2 shows a typical speed profile of a bus during peak and off-peak periods. It is clearly seen that during peak periods, a considerable amount of time is spent idling because of which the duration of the trip increases.

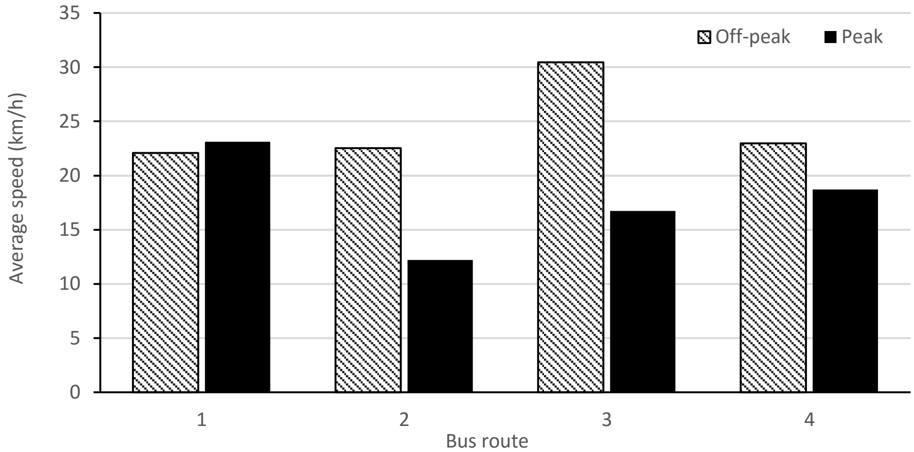

Fig. 1. Average speed during peak and off-peak periods along the four bus routes.

Table 2 shows the driving characteristics during peak and off-peak periods. It is seen that average running speed is higher in off-peak hours relative to peak periods, whereas the maximum speed and acceleration/deceleration characteristics remain almost same. Percentage of time spent in idling during peak hour is higher than during off-peak hour; percentage of time spent in other driving modes does not differ much. However, the number of stops per km increases drastically during peak periods relative to off-peak periods.

Table 2. Driving pattern in peak and off-peak periods.

Time period	V_1 (km/h)	V_2 (km/h)	V_{max} (km/h)	A (m/s^2)	D (m/s^2)	A_{max} (m/s^2)	D_{max} (m/s^2)	P_i (%)	P_a (%)	P_d (%)	P_{cr} (%)	P_c (%)	No. of stops/km
Peak	17.8	24.9	63.4	0.38	-0.53	2.31	-2.72	27.54	34.54	22.35	3.02	12.55	3.2
Off-peak	21.5	27.2	63.7	0.37	-0.52	2.28	-2.81	21.69	36.57	24.64	2.43	14.67	2.5

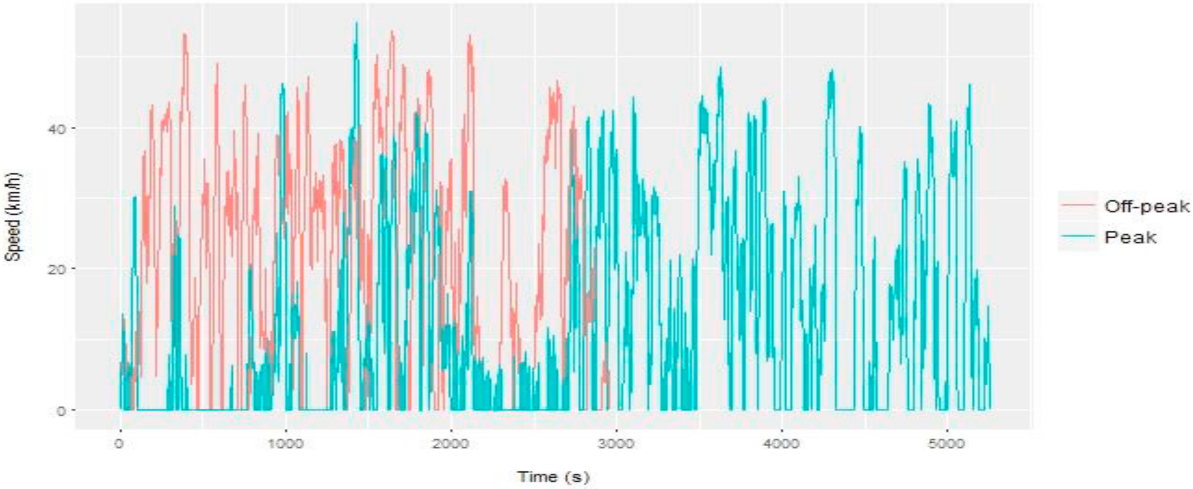

Fig. 2. Typical variation in instantaneous speeds during peak and off-peak periods during one trip.

5. Estimation of emissions

Vehicle specific power (VSP) has been found to have a high correlation with emissions and is widely used for estimating emissions from vehicles (Jimenez et al., 1999). Based on the instantaneous speed and acceleration, vehicle specific power is determined using the equation shown below,

$$VSP = v \times [a + g \times grade + g \times C_r] + \frac{1}{2}\rho_a \frac{C_D \times A}{m} \times v^3 \tag{1}$$

Where VSP is estimated vehicle specific power in kW/ton, v is the instantaneous speed in m/s, a is instantaneous acceleration in m/s^2, g is the acceleration due to gravity in m/s^2, *grade* is the gradient in %, C_r is the rolling resistance coefficient, ρ_a is the ambient air density in kg/m^3, C_D is the aerodynamic drag coefficient, A is the frontal area in m^2 and m is the vehicle total mass.

The equation 2 (USEPA, 2010b) was used to determine VSP mode of the bus, as given below:

$$VSP = \left(\frac{A}{M}\right) \times \mathrm{v} + \left(\frac{B}{M}\right) \times v^2 + \left(\frac{C}{M}\right) \times v^3 + \left(a + g \sin\theta\right) \times v \tag{2}$$

where A, B, C are the road load coefficients in units of (kW-second)/(meter), (kW-second^2)/(meter^2), and (kW-second^3)/(meter^3), respectively. The 'M' represents fixed mass factor in tonnes, 'v' is the vehicle speed in meter/second, 'a' is the acceleration in meter/second^2, 'g' is the acceleration due to gravity (9.8 m/s^2) and 'sin Θ' is the fractional road grade. The road load coefficients (A, B and C) depend on the weight of the bus and are obtained from equations given in MOtor Vehicle Emission Simulator (MOVES) model user guide (USEPA, 2010b).

Using the second-by-second VSP, the operating mode of the vehicle was determined. The emission rate of CO_2, CO, HC, and NO_x corresponding to each operating mode of the bus was adopted from the study by Zhai et al. (2008). Further, the time spent in each of the operating modes was used to determine the total emissions from one trip of the bus from origin to destination.

Figure 3 shows a comparison of percentage of time spent in each of the eight VSP modes for one trip each of route R3 during peak and off-peak periods. Clearly, significantly higher time is spent on VSP modes 1 and 2 (modes that include idling and low speeds) during peak hour as compared to off-peak hour.

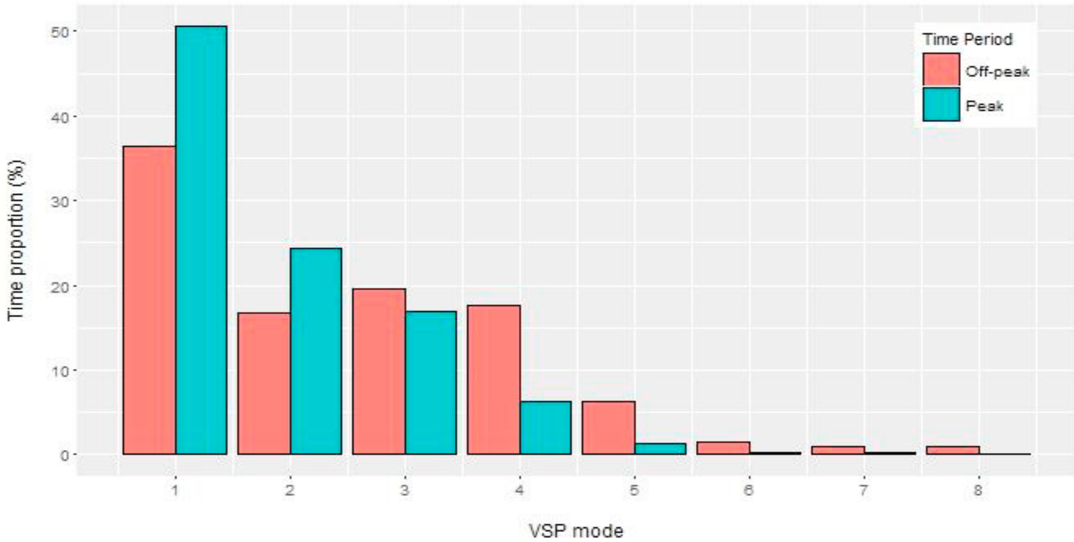

Fig. 3. Proportion of time spent in VSP modes during off-peak and peak periods.

The resultant total emissions of CO, CO_2, HC and NO_x along the four bus routes are shown in Table 3. Emissions of CO and CO_2 increase by about 16% in peak periods relative to off-peak periods, whereas HC and NO_x emissions increase by 37% and 21% respectively. This increase in emissions also indicates a corresponding increase in fuel consumption.

Table 3. Total emissions during peak and off-peak periods.

Bus Route no.	CO_2 (kg)		CO (g)		HC (kg)		NO_x (g)	
	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak
R1	32964	24307	123.51	92.99	7653.7	4593.3	457.98	331.73
R2	34807	30284	133.05	114.82	6808.3	5553	483.09	409.76
R3	57230	46221	218.94	175.37	12266	7322.1	816.23	608.51
R4	51338	54592	197.52	209.23	9750.6	10323	712.61	747.23

6. Effect of passenger load on emissions

The load on the bus varies as the bus travels from origin to destination with passengers boarding and alighting from the bus. Using the data from the ticketing machine, the number of passengers in the bus between two alternative stages was determined. Passenger count varied in the range of seven to sixty-three (excluding those having bus pass). The distribution of VSP considering the load of passengers was determined assuming an average person mass of 60 kg (Shome et al., 2014). The total emissions of CO_2 and NO_x were found to increase by 2.66 % and 2.07 %, respectively, whereas CO and HC showed small increase of 1.71% and 0.5%, respectively. Although not substantial, these results indicate the impact of passenger load on emissions.

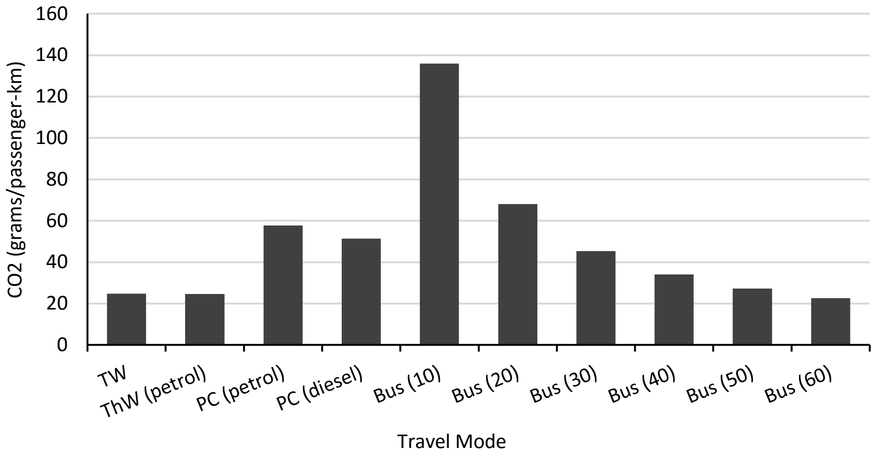

Figure 4. Emissions per passenger-kilometer for different modes (Note: number of passenger in bus is shown in parenthesis).

The per passenger emissions per kilometre is shown in Figure 4. The emission factors for two-wheeler (TW), three-wheeler (ThW) and passenger car (PC) were obtained from ARAI report (ARAI, 2008). The occupancy of two-wheeler, three-wheeler, and passenger cars was assumed to be one, three, and three, respectively. Results show that per passenger emissions from a bus with 40 passengers is lower than that of passenger cars and marginally more than that of two-wheeler and three-wheelers. However, it is also seen that bus with 10 passengers leads to significantly higher emissions per passenger.

7. Conclusions

This paper evaluates the driving characteristics of intra-city buses using real-world second-by-second GPS data of four routes during peak and off-peak periods. It is seen that significantly higher time is spent in idling mode during peak periods with low average speeds. Also, the number of stops per kilometer is higher during peak periods. Further, the estimated total emissions show a significant increase for all the pollutants during peak periods as compared to off-peak periods. Buses with less than 40 (20) passengers generate more emission/passenger-km than a motorized two wheelers (car with three passengers). Since most buses, particularly during off-peak periods, do not have such high ridership, the claim that bus travel is more sustainable with respect to emissions is questionable. Considering the magnitude of emissions, it may be worthwhile to adopt electric buses in cities. However, the necessary charging and maintenance infrastructure need to be setup for the electric buses to succeed in replacing the entire fleet of existing diesel buses.

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