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An Assessment of Two-Wheeler CO and PM_{10} Exposures Along Arterial Main Roads in Bangalore City, India

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Abstract: This study investigated 2-wheeler exposures to CO and PM_{10} along six standardized arterial main road stretches in Bangalore city in India during morning peak (9:00-11:00) and afternoon non-peak hours (13:00-15:00) using personal samplers. Background levels on a local street carrying no traffic and away from main roads were also monitored to determine the actual contributions of vehicular traffic to exposure. Road stretches were selected to compare exposures on two types of routes - inner arterials and outer arterials with different built form characteristics.

Results indicate that average background PM_{10} and CO concentrations were much lower than the respective averages of the 2-wheeler exposures as expected. While PM_{10} exposures for inner arterials were higher than for outer arterials ($p=0.007$), differences were much larger for CO ($p<0.001$). Since the average run speeds were comparable for the stretches, the variations in PM_{10} and CO could be attributed to different vehicular compositions and built form characteristics of the stretches, but this needs to be verified through further investigation. PM_{10} exposures during non-peaks were lower than during morning peaks ($p=0.02$). However, CO exposures were not very different between non-peak hours and morning peak hours ($p=0.138$) despite comparable average run speeds and shows that even lower traffic volumes during non-peak hours result in high exposures. Results of various bivariate models indicate that average run speed is a good predictor of CO exposures ($R^2=0.56$) but is only a minor predictor of PM_{10} exposures ($R^2=0.18$) in Bangalore.

Keywords: Carbon monoxide, exposure assessment, in-vehicle exposure, nephelometer, particulate matter, Personal monitoring.

1. INTRODUCTION

Bangalore is the fifth largest metropolitan region in India and is the capital of the State of Karnataka. The city has undergone rapid growth and transformation since the 1990s due to its integration into the global economy. According to the Census of India, the city's population has grown from 2.92 million in 1981 to 8.43 million in 2011. The rapid growth of Bangalore was not anticipated and the city has not been able to keep up with the demands for water, electricity and other infrastructure. This is very evident in the public transportation system, which depends entirely on the city's roads and has not been able to satisfy the needs of the city. The vehicular population has increased exponentially from about 0.15 million registered motor vehicles in 1981 to about 3.13 million in 2008 [1]. Thus, while the population of Bangalore almost trebled between 1981 and 2011, the vehicle population increased by more than 20 times during the same period.

Of the 3.13 million registered vehicles in 2008, the 2-wheeler population accounted for 71.5% and cars were 16.1% of the vehicle population [1]. The 2-wheelers in the city comprise a mix of 2-stroke and 4-stroke petrol motorcycles as well as scooters and mopeds. The high density and intermixing of slow and fast moving traffic has drastically reduced the level of service of many roads in the city leading to more frequent congestion at many locations. The average speed on certain main roads has reduced to between 13.8 km h^{-1} and 29.2 km h^{-1} in a study of travel speeds in different locations of Bangalore during peak hours [2].

Since 1991, the Government of India has sought to improve air quality through fuel quality improvements and tightening of vehicle emission norms to control vehicular air pollution in urban areas. Air quality nevertheless continues to be an area of concern in most urban areas of India as a result of the rapid increase in the number of registered vehicles. Particulate matter and sulphur dioxide concentrations in Bangalore have decreased and correspond to the incremental fuel quality and vehicle emission norms implemented. However, particulate matter and Respirable Suspended Particulate Matter (RSPM) concentrations are still above permissible standards [3].

Although ambient concentrations of a pollutant could be high, an individual's actual exposure is dependent on the specific concentration of the pollutant during the period of contact with the pollutant [4-6]. Air pollution exposures in a city or rural area were earlier estimated from stationary air quality monitors located outdoors when personal or portable

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monitors were not developed [4, 5]. Personal samplers used in later studies have shown exposure levels of carbon monoxide to be much higher when compared to fixed site monitors [7-9]. Akland *et al.* [7] have also shown high levels of pollutant exposures in certain commuter microenvironments even though time spent in them may be relatively low. Recent studies have indicated that vehicle-related pollutants are highly concentrated immediately downwind from major roadways - pollutant concentrations decay from the edge of a roadway by as much as sixty percent at 100 m downwind, drops to near background levels at about 200 m, and are indistinguishable from background levels at 300 m [10]. The high spatial variability of pollutants in the context of vehicular emissions is thus an important factor in choosing an appropriate methodology to estimate in-vehicle or commuting exposures.

Commuting is characterized by short time intervals with high levels of pollutants compared to other micro-environments such as indoor or other outdoor environments. Exposure while commuting is influenced by other factors such as mode of transport, type of air-conditioning and travel speed. Fixed-site monitoring data of ambient pollutant levels are therefore not suitable for accurate exposure assessment of commuters. Electrochemical sensor based personal CO monitors have been used extensively to assess commuter exposure in ambient conditions in several studies [9, 11]. Gravimetric techniques are being used for measuring personal exposures to Particulate Matter (PM), but short measurement durations for commuting might not capture adequate mass of particulates. In contrast, nephelometric or photometric techniques are capable of measuring PM concentration in real time [12]. These are also lightweight and require less power; which makes them ideal for measurements of personal commuter exposure.

Several in-vehicle exposure studies have shown significant differences in exposures to CO based on transport mode used, type of route (traffic conditions, street location, function and configuration), travel speed, season, wind speeds, ventilation mode / use of air-conditioning [13]. Saksena *et al.* [14] observed that exposures to PM_5 and CO in Delhi were highest during travel by 2-wheelers (PM_5 levels of 2860 $\mu g\ m^{-3}$ and CO levels of 19 ppm) while PM_5 was lowest in cars (370 $\mu g\ m^{-3}$) and CO lowest in buses. Saksena *et al.* [15] also compared PM and CO exposures of various modes in Hanoi, Vietnam, and found that mobike riders have the highest exposures to both pollutants compared to cars, buses or pedestrians.

Zhao *et al.* [16] and Bevan *et al.* [17] also found that exposures to CO and PM_{10} are higher in commercial street situations (urban versus suburban routes) for pedestrians and bicyclists. Calm weather produced higher CO & fine PM than windy weather but higher wind speed increased coarse PM levels in Kuopio, Finland [18].

2. STUDY OBJECTIVES

The purpose of this study was to investigate the levels of 2-wheeler commuter exposures to CO and PM_{10} along stretches of arterial main roads in Bangalore city in India using personal samplers. The focus of the study was on 2-wheelers since this category of vehicles makes up the largest vehicle fleet of the city. Moreover, 2-wheeler riders are more directly exposed to air pollutants as there is no protective enclosure as in cars or buses and other studies [14,15] point to higher exposure levels for this vehicle category.

The study was designed to establish the differences between commuter exposures during morning peak and afternoon non-peak periods as well as between internal and outer arterial stretches with different built form characteristics. The study also examined CO and PM_{10} exposures as a function of speed.

As discussed earlier, very few studies are available on exposures of 2-wheeler commuters, which make up a significant proportion of the vehicular fleet in most South Asian and South East Asian countries. This study thus is an attempt to contribute to data on 2-wheeler exposures to PM_{10} and CO in this region. Available studies in other parts of the world focus mainly on in-vehicle commuter exposures for cars and the results are not directly relevant to these countries.

3. METHODS

Personal sampling was carried out by riding a 2-wheeler along six stretches of arterial roads in Bangalore city using an electrochemical sensor Langan T15d personal sampler for CO and a light scattering MIE pDRAM 1100 nephelometer (pDR) for PM_{10}. The vehicle used for the runs was a 2001 model four-stroke, petrol-engine Bajaj Sapphire two-wheeler. The CO and PM_{10} instruments were operated passively and strapped across the shoulder of the driver of the 2-wheeler. Data used for the analysis were gathered during a winter season in Bangalore. The use of personal samplers for exposure measurements thus captures short-term fluctuations of pollutants resulting from spatial differences and the influence of travel speed.

Relative Humidity (RH) and temperature were also monitored using a HOBO temperature/RH data logger and trip speeds recorded for each run. The CO and PM_{10} personal samplers, along with the HOBO data logger were strapped across the shoulder of the driver of the 2-wheeler for concurrent monitoring of the commuting microenvironment. The CO and PM_{10} samplers have in-built data loggers and the logging interval was set at 30 s for both. RH and temperature logging intervals were set at 1 min.

The pDR is calibrated by the manufacturer using Arizona Test Dust (ISO 12103-1), which has a wide size distribution covering the entire detected size range of the pDR. Since the size range of particulate emissions from traffic is different from the reference size distribution, a secondary calibration was carried out for measuring traffic-related particulates to obtain more accurate mass concentration data. This was done by calibrating the instrument against a high-volume gravimetric sampler for PM_{10} located at the boundary site of a building close to a street carrying moderately high traffic in Bangalore. Based on this calibration, a factor of 0.673 was applied to all recorded values of the pDR. The pDR was also zeroed using a Z-pouch attached to a small High Efficiency Particulate Air (HEPA) filter supplied by the manufacturer before every circuit run.

The selected stretches ranged from 4.8 to 7.6 km in length. Of the six stretches selected, two stretches were along the outer arterial ring road of the city. The outer arterial road is characterized by service roads on both sides, and low height buildings which provide greater overall road width and pollutant dispersion potential. The other four arterial stretches were along the inner part of the city and carry mixed traffic consisting of petrol 2-wheelers, Liquefied Petroleum Gas (LPG) or petrol three-wheelers, petrol and diesel cars, and diesel buses. These inner roads do not have any service roads and the overall ratio of road width to the height of the buildings alongside is much higher than for the outer arterial road stretches. The selected stretches are shown in Fig. (**1**).

Runs were carried out in sequence, beginning with one internal route, the two outer routes next, and then three inner routes forming a circuit. These six runs were carried out between 9:00 and 11:00 am, which is considered as the morning peak period in Bangalore. This circuit was repeated during the same day between 1:00 and 3:00 pm, which is the afternoon non-peak period. In all 30 peak-hour and 30 non-peak hour runs were carried out.

Background levels were also measured at a location about 150 m away from traffic carrying roads. These measurements were recorded for a period of about 5 min before or after every circuit run. Each PM_{10} measurement for a run or background average was logged as a different tag number, the tag assigned based on the start of the logging period. This facility was not available with the CO and

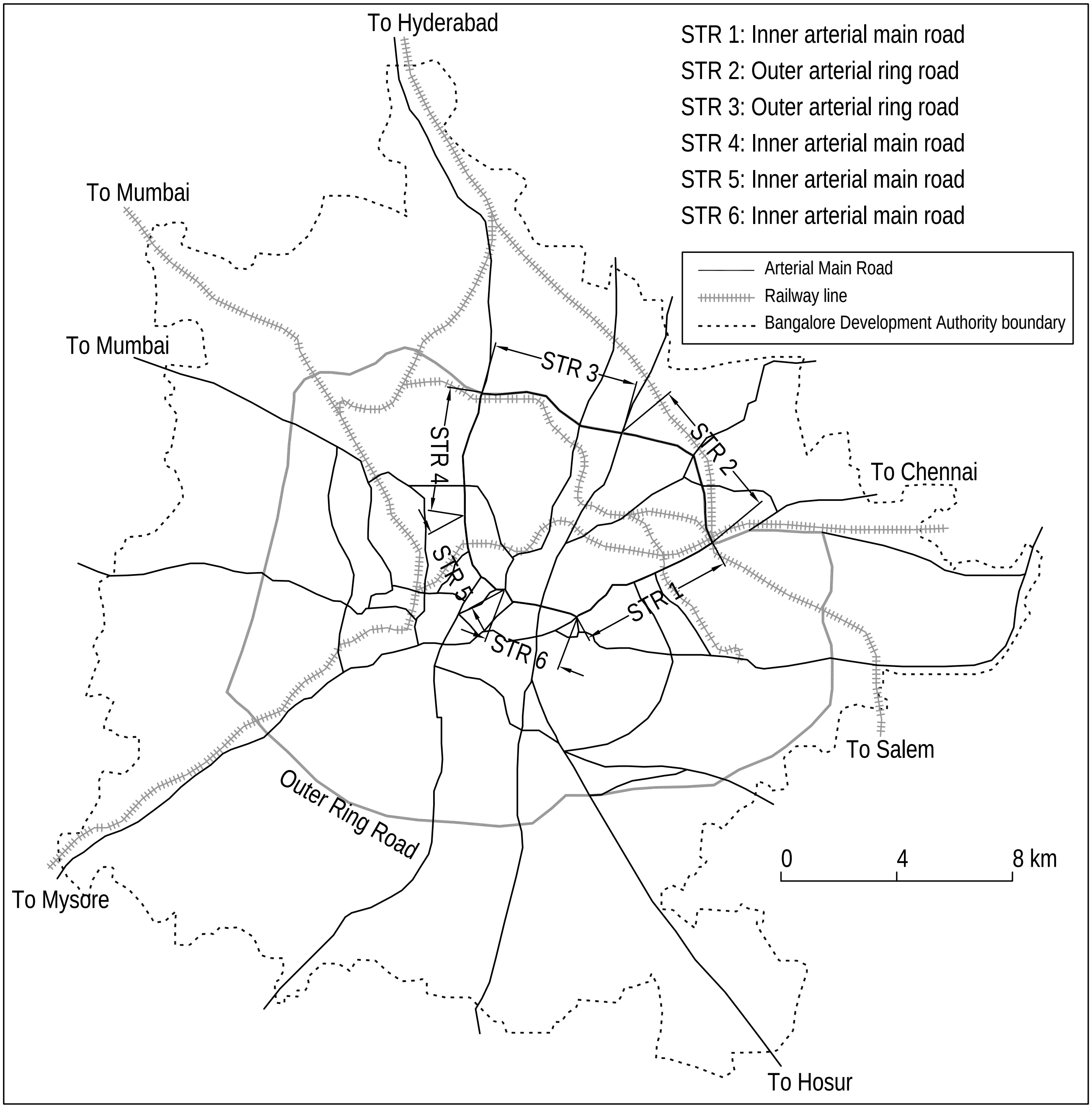

Fig. (1). The six stretches selected for the study.

RH/temperature instruments and the data were manually linked to each corresponding tag after downloading data into a computer. At the beginning and end of each measurement, the time and odometer readings were also recorded to estimate run speeds. Traffic levels and composition were also noted during each run, albeit qualitatively.

4. RESULTS

The 30 s readings of CO and PM_{10} exposures for one stretch are shown in Fig. (**2**) below. These readings of CO and PM_{10} were averaged for the duration of the measurement period for each run to arrive at the mean instantaneous exposures for that individual run.

PM_{10} measurements reported here have been adjusted using the calibration factor from the collocation exercise described in the previous section. Humidity levels above 60% are known to affect readings from the nephelometer [19, 20]. During our survey, the measured RH had a mean of 47% and standard deviation of 11%. Therefore, it was not necessary to correct the PM_{10} data for RH effects.

The 30 s values for each individual run are likely to be serially correlated and geometric means for each run were calculated. The mean instantaneous exposures (arithmetic and geometric means) and other descriptive statistics for PM_{10} and CO are summarized in Table **1**.

The results indicate that average background PM_{10} (AM = 150 $\mu g\ m^{-3}$) and average CO (AM = 0.4 ppm) concentrations measured away from traffic carrying roads were much lower ($p<0.001$, two-sided) than the respective mean instantaneous commuter exposures of 2-wheelers (AM = 375 $\mu g\ m^{-3}$ and 6.6 ppm, respectively). While the mean PM_{10} exposure for inner arterials (AM = 398 $\mu g\ m^{-3}$) was higher ($p<0.007$, two-sided) than outer arterials (AM = 329 $\mu g\ m^{-3}$), differences were much larger for CO (AM = 7.9 ppm for inner and AM = 3.9 ppm for outer; $p<0.001$, two-sided). Since average run speeds were only marginally higher on outer roads (28.9 km h^{-1}) than on inner roads (24.6 km h^{-1}), the variations in PM_{10} and CO can be attributed to different built form characteristics - there is greater potential for dispersion of pollutants due to the lower ratio of the height of buildings to the overall width of the outer arterial road. These differences could also perhaps be due to differences in vehicular compositions - the outer arterial stretches carry a larger proportion of heavy diesel trucks and buses while the inner arterials carry a mixed vehicle composition with petrol and diesel vehicles. PM_{10} exposures during non-peaks (AM = 347 $\mu g\ m^{-3}$) were lower ($p<0.02$, two-sided) than during morning peaks (AM = 403 $\mu g\ m^{-3}$) despite statistically insignificant differences in average speeds. Statistical differences in CO exposures ($p=0.138$) between non-peak hours (AM = 6.0 ppm) and morning peak hours (AM = 7.1 ppm) were however not evident.

5. MODELS OF EXPOSURE

Commuter exposures to PM_{10} and CO are correlated with health effects and identifying various factors that contribute to commuter exposures would therefore provide valuable insight to address the issue. Statistical models have been developed in several locations to predict average concentrations of CO inside a vehicle on segments of highways [13, 21]. Ott *et al.* [21] examined the explanatory power of nine variables and predicted the average CO exposure per trip as a function of just two variables. Flachsbart [13] developed models with three variables (adjusted $R^2=0.69$) in non-linear combinations: average CO concentration inside the cabin for one link; wind speed and direction; and either travel time, vehicle speed or CO emission for a previous travelled link.

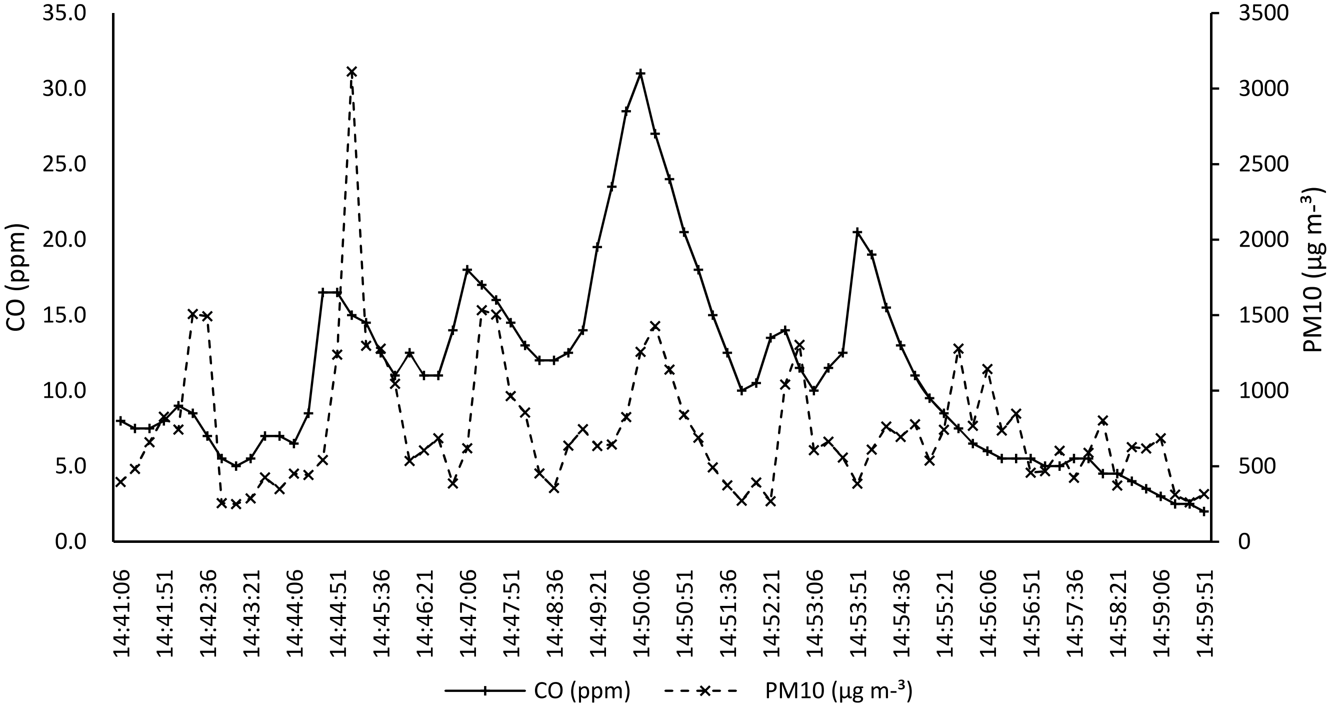

Fig. (2). Instantaneous CO and PM_{10} exposures at 30 s intervals for one stretch.

Table 1. **Descriptive Statistics of Mean Instantaneous PM$_{10}$ and CO Exposures**

	Background	Commuter	Internal Arterial Roads	Outer Arterial Roads	Peak Hour	Non-Peak Hour
PM$_{10}$ (μg m^{-3})						
N	20	60	40	20	30	30
AM (GM)	150 (140)	375 (363)	398 (388)	329 (318)	403 (395)	347 (334)
SD	64	95	91	88	84	98
CV (%)	43	25	23	27	21	28
t-Stat (p, two-sided)	-11.9 (<0.001)		2.8 (0.007)		2.4 (0.020)	
CO (ppm)						
N	10	60	40	20	30	30
AM (GM)	0.4 (0.3)	6.6 (5.9)	7.9 (7.5)	3.9 (3.7)	7.1 (6.4)	6.0 (5.5)
SD	0.4	3.0	2.6	1.4	3.2	2.6
CV (%)	93	45	33	36	45	43
t-Stat (p, two-sided)	-15.4 (<0.001)		7.6 (<0.001)		1.5 (0.138)	
Run Speed (km h^{-1})						
N	Na	60	40	20	30	30
AM	Na	26.0	24.6	28.9	25.3	26.7
SD	Na	4.7	4.4	3.9	4.4	5.0
CV (%)	Na	18	18	14	17	19
t-Stat (p, two-sided)	Na		-3.9 (<0.001)		-1.1 (0.27)	

AM: Arithmetic Mean, GM: Geometric Mean, SD: Standard Deviation, CV: Coefficient of Variation.

Average commuter speed has been identified as an important factor that contributes to CO exposures. Higher automobile speeds of 60 m h^{-1} in Washington reduce commuter exposures to CO by about 35% when compared to speeds of 10 m h^{-1} [22]. CO exposure inside a car was strongly affected by travel time and average vehicle speed, which were assumed to be indirect measures of traffic flow and average speed of surrounding traffic [13]. Travel speed rather than ambient temperature was the dominant factor affecting CO emissions. Commuter exposure to particulate matter, especially coarse fractions, however, has not been as significant. Alm *et al.* [18] reported higher fine PM (0.3-1μm) and CO exposure levels at slow speeds (<26 km h^{-1}) than faster speeds (>26 km h^{-1}) but speed did not have any clear effect on coarse PM (1-10 μm) exposure levels.

As part of this analysis, it was the intention to assess the extent to which average speed could be an indicator of commuter exposures to CO and PM$_{10}$. Models that predict PM$_{10}$ and CO exposures as a function of commuting speed would be valuable for informing policy on decisions to mitigate vehicular emissions without the need for expensive monitoring of these pollutants. This is based on the premise that emissions from vehicles moving at speeds lower than the recommended optimum speeds are higher than for faster moving vehicles, and secondly, lower vehicle speeds on the roads are likely to result in more congested conditions leading to less dispersion of pollutants. Therefore, slow speeds of vehicles would result in greater exposure levels to pollutants. In actuality, traffic flow and average speeds on the selected routes could also be affected by traffic signals. The duration and number of 'green times' vary for each stretch irrespective of traffic conditions but this was not accounted for in this analysis but rather only the total time taken for completing the stretch was considered and the stop time at signals was not controlled for.

5.1. Correlation Between Variables

The Pearson coefficients of correlation between the variables of run speed, CO and PM$_{10}$ are presented in Table **2**. The data indicate that PM$_{10}$ and CO are positively related and to a reasonable degree (r = 0.35). However, the correlation is not so strong that CO can be used as a reliable surrogate indicator for PM$_{10}$. As expected, both PM$_{10}$ and CO are negatively related with speed, the degree of the relationship being higher for CO (r = -0.47) than for PM$_{10}$ (r = -0.25).

Table 2. **Pearson Coefficients of Correlation**

	PM$_{10}$	CO	Run Speed
PM$_{10}$	1.00		
CO	0.35	1.00	
Run speed	-0.25	-0.47	1.00

5.2. Speed Models

The bivariate statistical models of 2-wheeler commuter exposure to CO and PM$_{10}$ developed in this study are based on the sixty runs that were carried out using speed as an independent variable. CO and PM$_{10}$ concentrations were also corrected for background levels and modeled. The models were fitted to the data using Ordinary Least Squares regression analysis. An evaluation was carried out for linear, exponential, power and parabolic relationships.

The exponential models are the best models to predict PM_{10} and CO mean instantaneous exposures using speed when R^2 values, *F* and *t* statistics are considered. When adjusted for background levels, the R^2 values increase slightly indicating the high background levels of PM_{10}. There are no differences in the R^2 values for CO since background levels of CO are relatively less than for PM_{10}. When outliers are removed from the data, the R^2 values improve significantly. The models for CO and PM_{10} adjusted for background levels and with outliers removed are presented in Figs. (**3**, **4**).

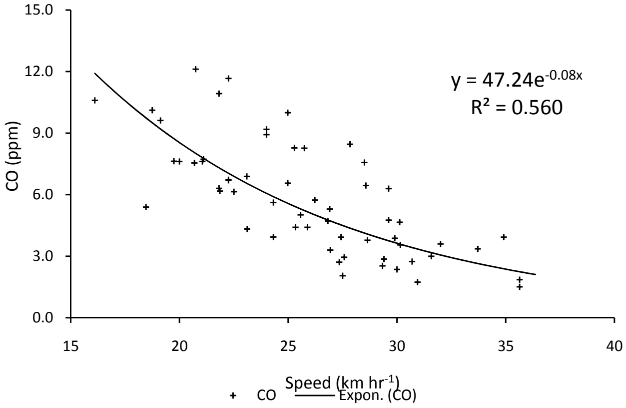

Fig. (3). Exponential bivariate model of CO and speed.

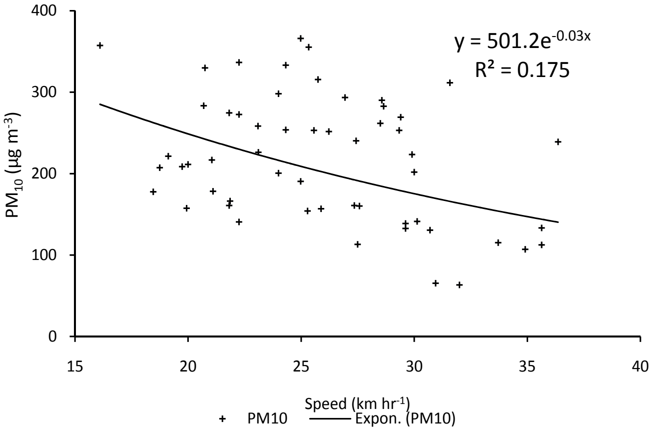

Fig. (4). Exponential bivariate model of PM_{10} and speed.

6. DISCUSSION AND CONCLUSIONS

This study provides evidence that background levels of CO and PM_{10} are significantly lower than levels while commuting. This reinforces the argument that using fixed site monitors to establish commuting exposures is not likely to provide an accurate representation of exposures while commuting.

Differences in both PM_{10} and CO exposures are evident between inner city roads and stretches along the outer arterial ring road of the city. Although vehicular densities in these stretches were not estimated during the study, the marginal differences in speed when this study was carried out is an indicator that levels of congestion were not very different between these stretches, which are similar in terms of capacities. The lower exposures along the outer arterial road that has very different built form characteristics suggests that dispersion of vehicular emissions has to be taken into account in urban land use policy formulation in terms of densification or height regulations along arterial roads. The outer arterials however, carry a larger proportion of heavy diesel vehicles compared to the inner arterial stretches with a mixed composition of mainly petrol vehicles. Further studies are needed to control for this factor before drawing any firm conclusions.

Peak hour commuting exposures are not significantly different from non-peak hour exposures for CO. Since CO is correlated with traffic emissions, this points out that even lower traffic volumes during non-peak hours result in exposures that are as high as higher traffic volumes during peak hours despite similar speeds and vehicular densities. This suggests that better engine technology and fuel quality policies are required to bring down vehicular emissions. The low vehicular speeds also points towards a higher degree of congestion. Policies to reduce traffic density through incentives to use public transport, or policies to reduce travel demand are possible measures to reduce emissions.

Various models of CO and PM_{10} exposures as a function of vehicle speed were examined in our study. Results indicate that average run speed is a good predictor of CO exposures (R^2=0.56) but is only a minor predictor of PM_{10} exposures (R^2=0.18) in Bangalore. The speed models show that with increase in speed, exposure levels are reduced. When speeds increase from the lowest recorded run speed of 16.1 km h^{-1} to the maximum recorded run speed of 35.6 km h^{-1}, exposures decrease by 81.3% for CO and by 49.5% for PM_{10}. These decreases are far higher than those seen in the study by Flachsbart *et al.* [22] and indicates that the number of stops at intersections, which contribute to lower run speeds and also to higher instantaneous exposure levels, are an important factor that contribute to higher mean exposures.

Measures to increase average vehicular speeds through synchronized traffic signals or intelligent vehicle actuated signals could be implemented along major arterial roads to improve speeds and reduce stops at signals. Other traffic management measures that reduce congestion and improve speeds such as lane movement, road and junction geometry improvements, preventing parking and stopping on arterial roads, etc., could also be implemented to improve speeds.

The exposures measured as part of this study reflect the mean instantaneous exposures to PM_{10} and CO at the breathing zone of a 2-wheeler rider. At the time of the study, the driver of a 2-wheeler in Bangalore was not required to wear a helmet but the government of Karnataka has recently made it mandatory for the driver of a 2-wheeler to wear a helmet. The helmet is mandated primarily for the purpose of safety although the pillion rider is not required to wear any such protective equipment. The helmet is not required to provide any filter that could potentially reduce exposure to pollutants. It would be necessary for further research to ascertain whether wearing protective headgear with a visor or similar barrier would reduce the exposure to pollutants and to what degree. The outcomes of such research could inform policy makers to specify the use of headgear for the driver as well as the pillion rider. Further similar exposure studies are needed for other modes of transport in the city to ascertain the relative exposure levels and to see what policy responses could reduce these exposures.

There are several limitations of our study, which could affect the explanatory power of the models presented. The average speeds measured for each commute could be an artifact of the characteristics of the test vehicle's driver and not representative of the true average speeds of 2-wheeler commuters. As mentioned earlier, the 'green times' at signals were also not taken into account but this could be a significant factor affecting the models.

Wu *et al.* [23] report a weak but significantly positive correlation (Pearson's correlation coefficient = 0.13) between the ratio of readings of collocated pDR's in passive and active heating modes and wind speed, suggesting that the passive pDR may oversample under high wind conditions. Thorpe and Walsh [24] found that air velocity had little monitor response for stone dust, but the ratio of monitor response decreased with velocity increase for pine dust and is attributed to larger particle size as well as higher inertial properties of pine dust. Since the pDR used in the study was in an exposed environment, across the shoulder of the driver, this would result in an effective wind speed approximating the vehicle speed. This, coupled with any effect of turbulence, could therefore also affect the readings of PM_{10} for 2-wheeler commuters. Further research is required to assess exposures that are measured with the instrument without being in the direction of vehicle movement, such as across the back of the driver or across the shoulder of a pillion rider. Thorpe and Walsh [24] have observed the varying responses of pDR monitor orientation on temporal uniformity of measured dust concentrations (upright, on its side, on its back). The instrument sampled more effectively when placed on its side inside an enclosure. This is another aspect that needs to be researched further, especially when the instrument is used for 2-wheeler commuter assessments.

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CONFLICT OF INTEREST

None declared.

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