IMPACT OF BUS RAPID TRANSIT ON URBAN AIR POLLUTION: COMMUTER'S EXPOSURE TO $PM_{2.5}$ IN AHMEDABAD

Shivanand Swamy[1] , Madhav Pai[2] and Shelly Kulshrestha[3]

Abstract

There is a growing concern about the health impacts of transportation leading to curiosity among commuters about their exposure to air pollutants during transit. The paper examines a critical pollutant, Particulate Matter ($PM_{2.5}$) and explores road based transport modes with an objective to minimize risk of exposure to pollutants. The study is conducted on a 10 km stretch in the city of Ahmedabad, India using Bus Rapid Transit System (BRTS) buses, city buses and other motorized and non-motorized modes. It defines variation in $PM_{2.5}$ concentration levels while commuting in different modes, during various seasons (winter, summer and monsoon), location as well as varying time of the day.

The study gives a comparative overview of real time exposure to $PM_{2.5}$ across nine transport modes. In-vehicle exposure in air conditioned (AC) BRTS buses showed lowest $PM_{2.5}$ concentration levels. Factors such as segregation, elevated height of exposure and the presence of air-conditioning were seen to favor lower exposure levels. In all the modes, the mean concentration level of $PM_{2.5}$ was highest during winter (M=390µg/m^3, SD=187) and lowest during the monsoon period (M=115 µg/m^3, SD=107). Another consistent observation during the day was lowest $PM_{2.5}$ levels during the afternoon and highest during the evening trips. This has relevance for commuters with respiratory problems in scheduling their travel plan. While walking, internal street trip recorded lower $PM_{2.5}$ levels as compared to the main road with traffic. Real time information to commuters would increase their awareness for choosing the mode with lower exposure levels. The paper provides a platform to influence policy decisions for promoting segregated public transport considering the health perspective of commuters.

INTRODUCTION

Ahmedabad, with a population of 5.5 million and an area of 466 sq. km (180 sq. miles) is the 7th largest city in India and a major industrial and commercial hub. The city has grown by 144 per cent (in area) and 58 per cent (in population) since 2006. Vehicular growth has also been tremendous. The annual growth rate of motorized vehicles registered in the city is about five times higher than that of the city population (24 per cent vs 4.7 per cent). In 2011-2012, 206,749 vehicles were added to the existing vehicle population of 1.96 million. 71 per cent of the newly registered vehicles were two-wheelers, followed by four-wheelers (25 per cent), autorickshaws (2 per cent) and buses/ trucks (0.1 per cent). Ahmedabad has been grappling with issues of congestion, pollution and an increasing floating population. With the launch of a national city modernisation scheme-Jawaharlal National Urban Renewal Mission (JnNURM) in 2006, the city has fast tracked the urban development process with key interventions in the transportation sector. These initiatives included restructuring of the road network, conversion of autorickshaws and buses to Compressed Natural Gas (CNG), augmenting public transit facilities like increased bus fleet under Ahmedabad Municipal Transport Service (AMTS) and introduction of Bus Rapid Transit System (BRTS).

This study focuses on monitoring commuter's exposure to $PM_{2.5}$, one of the key pollutants recognized for causing adverse health impact. Mode choice, time of travel or other travel pattern is seldom based on pollution studies. The study assesses in-vehicle $PM_{2.5}$ concentration levels in nine road-based transport modes, which are being commonly used by Ahmedabad citizens. The paper

[1] Professor and Executive Director, Centre of Excellence in Urban Transport, CEPT University, Ahmedabad , India, Email: shivanand.swamy@gmail.com
[2] Madhav Pai, Director, EMBARQ India, Email: mpai@embarqindia.org
[3] Shelly Kulshrestha (Corresponding Author), Senior Academic Associate, CEPT University, Ahmedabad, Email: shelly.kul@gmail.com

gives a comparative overview of the $PM_{2.5}$ levels and explores key factors which contribute to commuters' exposure in the urban transport microenvironment. It attempts to support policies for fostering transport modes and practices which minimize the risk of particulate exposure during transit.

1. LITERATURE REVIEW

1.1 Exposure to $PM_{2.5}$ - A Concern for Commuters

Exposure to $PM_{2.5}$ is of concern as particles smaller than or equal to 2.5 micrograms easily enter the respiratory tract reaching the alveoli. There is substantial literature which suggests that continued or even short term exposure to elevated levels of $PM_{2.5}$ leads to adverse respiratory (allergies, asthma, bronchitis, coughing, shortness of breath, decreased lung functions, lung cancer etc.) and cardiovascular health impacts (Brook, et al., 2010); Pope III & Dockery, 2006; Laden et al., 2006). It is of critical concern for susceptible individuals like people with heart and lung disease, children and the elderly as even short- term exposure can lead to adverse health impacts (Dominici, et al., 2006; Bell, Ebisu, & Belanger, 2007).

Particulate pollution on the road is mainly from sources like fuel combustion, wear and tear of vehicle body (brake lining, tyres), re-suspension of road dust, chemical reaction etc. The level of $PM_{2.5}$ concentration in motorized modes can vary depending on the infiltration from the ambient environment and self-pollution of the vehicle, dominant source of self-pollution being the tailpipe and the engine crankcase (Hill, Zimmerman, & Gooch, 2005). Multiple factors influence commuter's exposure levels including vehicle design, vehicle age, fuel type, position on the road, vehicle upholstery, passenger capacity, speed, acceleration activities, ventilation, etc. Other aspects like exposure height (position of breathing zone), meteorological factors (wind-speed and direction, humidity and temperature), time of the day, seasons, number of intersections, location (route/path followed by individuals) and pollution sources also influence exposure levels (Wohrnschimmel, et al., 2008; Adams et al., 2001; Kaur et al., 2007).

1.2 Assessment of Exposure to PM2.5 in the Transport Environment

Though average trip length in Ahmedabad is about 5 kms, which is comparatively shorter than other metro cities (CoE, 2013), exposure to elevated $PM_{2.5}$ levels and other pollutants is critical especially for the sensitive group. Exposure studies are useful when monitoring happens in close proximity to the commuters allowing them to identify those critical moments when the pollutant level exceeds the limit, even for a short duration. As most of the pollution data at the city level is generated through fixed monitoring stations (where the instruments are placed at a particular height or on rooftops), it has limited applicability for assessing an individual's exposure level. Fixed monitoring stations underestimate the pollution concentration level experienced by commuters (Adams et al., 2001; Kaur et al., 2007). This study preferred carrying out real time monitoring using portable monitors. As the pollutant concentration level is seen to vary with transport related micro-environment, multiple road based modes were selected for spatial real-time monitoring (Wang & Gao, 2010; Sabapathy, Ragavan, & Saksena, 2012).

2. MATERIAL AND METHODS

2.1 Modes and transit facilities

The study covered all dominant road-based modes including BRTS buses (AC and non-AC), city buses, private four-wheelers (AC and non-AC), three-wheelers, two-wheelers, cycles and pedestrians. Public transit facilities like bus stations were also included for monitoring to account for $PM_{2.5}$ exposure during the waiting period. To understand the usage of modes in the city, information was gathered through a few recent transport studies. Given below is an overview of the modes and bus stations in Ahmedabad.

Public Transport

The public transport in Ahmedabad consists of the city bus service and BRTS. It accounts for only 10 per cent of the total trips in the city (*10*). The city bus service is operated by AMTS and consists of 827 buses (174 routes, 1,688 bus stops). The total network is 550 km long and has a ridership of 600,000 passengers per day. It covers about 92 per cent of the total developed municipal area.

BRTS is operated by Ahmedabad Janmarg Limited. Started in 2009, it currently covers 86 kms (131 bus stations). The system functions with segregated bus lanes, median bus stations, level boarding and alighting, high frequency (2-5 minutes), low fares and a real-time passenger information system. It has a ridership of 125,000 passengers per day.

Private Transport

Ahmedabad has a substantially high number of private vehicles (cars and two-wheelers) constituting around 90 per cent of the total registered vehicles in the city. Private vehicle population is about 1.7 million (0.2 million cars and 1.5 million two-wheelers). Both the modes are growing at 8 per cent per annum and four-wheelers have more than doubled during the last decade (*10*). Two-wheelers are the most popular mode accounting for a third of the total trips in the city

Intermediate Public Transport (IPT)

Three-wheelers including auto-rickshaws and shared rickshaws are the main IPT modes operating in the city. There are 112,515 auto-rickshaws operating in the city, accounting for 9 per cent of the total trips. Their population is growing at 11 per cent per annum (*10*). Three-wheelers pose stiff competition to buses due to their easy availability and affordability. While auto-rickshaws operate in all parts of the city, shared autos are common in the eastern part.

Non-Motorized Transport (NMT)

Walking and cycling are the prevalent means of commuting in Ahmedabad. They account for 34 per cent of the total trips. Studies show that 50 per cent of the BRTS commuters prefer to walk for access and egress. Average walk trips are about 2 km and bicycle trips are about 3 km length in Ahmedabad (CoE, 2013).

Bus Stations

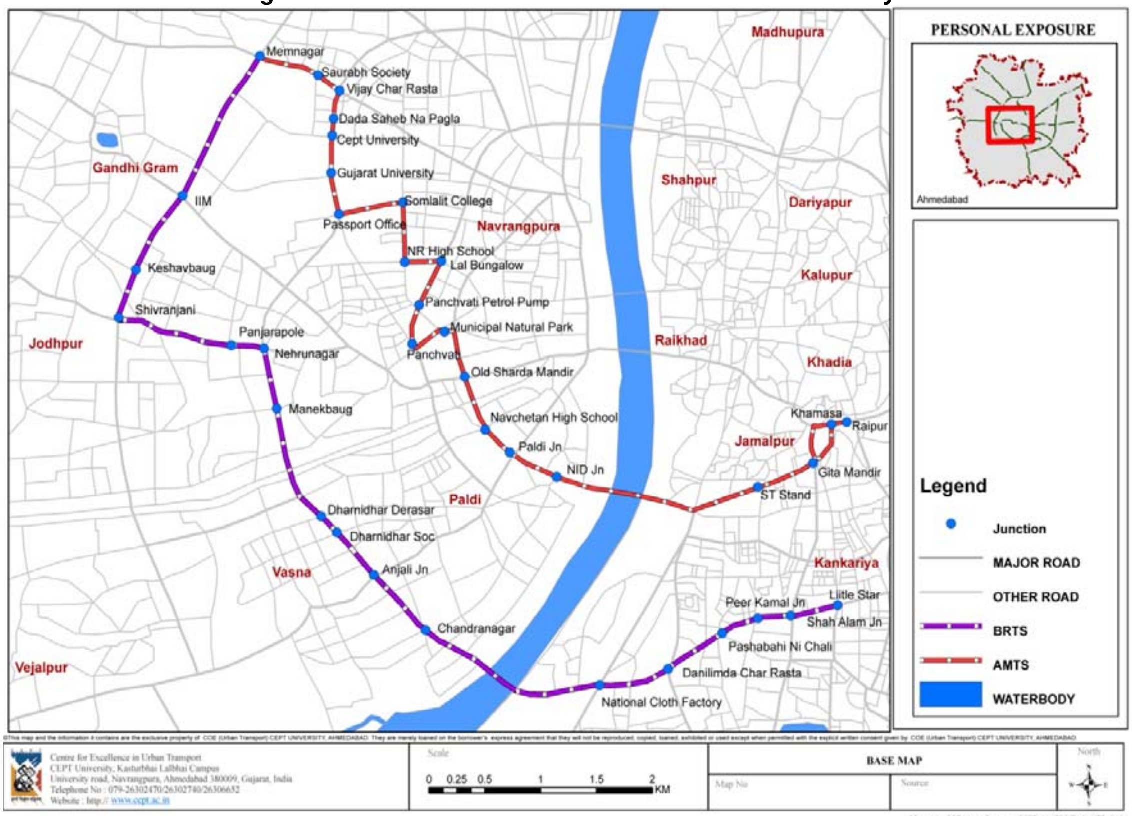
Ahmedabad's public transport system has two types of bus stations- median and curb side. BRTS stations have median location, high plinth (900 mm), at-grade approach, off-board ticketing facilities and tensile wires defining its exterior. Most of these stations are located near the junction with synchronized signal phasing for pedestrians. AMTS bus stops are located on the curbside of the road. They are a mixture of signposts and temporary structures.

2.2 Study Corridor

The study corridor was finalized after conducting trial runs using AMTS and BRTS buses. The selection criteria considered coverage of both eastern and western parts of the city defined by Sabarmati River; mix of land-use and income groups; completed corridors without any major ongoing civil work activities (construction, road-widening etc.) and inclusion of continuous routes for both modes.

The BRTS corridor extended from Memnagar to Kankaria Telephone Exchange covering a length of 10.56 km and 16 stations (Figure 1). A parallel corridor with similar Right of Way (RoW) was selected for monitoring exposure levels on an AMTS route. It extended from Memnagar to Raipur Darwaza covering a length of 9.6 km with 28 stops.

Figure 1 BRTS and AMTS routes selected for the study.



2.3 Sampling Design

The measurements were done in three phases (December 2011-January 2012; April 2012-May 2012 and June 2012-July 2012) representing winter, summer and the monsoon period. In each phase, a similar monitoring schedule was maintained covering all modes and sample bus stops. All modes were surveyed for three time slots in a day comprising of the morning peak (8:30 AM-11 AM), the afternoon off-peak (1:30 PM-4:00 PM) and the evening peak (6:30 PM-9:30 PM).

Monitoring was also conducted at bus stations during the waiting period. Additional surveys included measurement of $PM_{2.5}$ levels while walking on the main and internal roads, across road cross-section and with variation in elevation levels. 20-minute recordings were done at each point including footpaths, cycle tracks (where available), mixed lanes, railings/ edge of the BRTS lane and the center of the BRTS lane.

In all, the study consisted of 45 days of survey spread over three seasons. It summed up to 254 hours of in-vehicle monitoring involving 30-36 one-way trips in each of the nine modes (except walk trips, which were 26 one-way trips). In addition, the survey included 70 hours of monitoring at the bus stations during the peak and off-peak hours.

2.4 Monitoring Equipment

Two handheld photometric instruments-"Dust Track TM 8532" were used in the study for recording realtime $PM_{2.5}$ concentrations. Along with this, GPS instruments-"Garmin eTrex" and "Temperature–Relative Humidity Recorder (RH Temp101A)" helped to assign the location track point and the MET condition.

The Dust Track (DT) instruments (4.9x4.75x12.45 inches/ 12.4x12.1x31.1 cm) recorded the $PM_{2.5}$ concentrations at 5-second intervals and provided data on average, minimum and maximum readings in $\mu g/m^3$ during the trip. The DT instrument is based on technology using a light scattering sensor wherein a beam of laser light measures the particles in air. It uses an equation to convert the observed light deflection into an estimate of mass concentration in real time. DT instruments can measure particles in the range of 0.001 to 150 mg/m^3. Data logger (RH Temp101A) recorded temperature and relative humidity.

The DT instruments were operated as per the manual guidelines by a trained team of four people. The instruments were zero calibrated and the impactor plate was cleaned after every round trip. The display time in all instruments was synchronized daily. While monitoring, the DT instruments were kept close to the inhalation level. During each trip, the team recorded information related to waiting time, occupancy levels (in case of public transport), traffic condition and the surrounding polluting activity.

DT instruments were adjusted to record at 10-second intervals. The average number of samples recorded for one-way trips ranged from 100-300 in motorized modes and increased up to 1000 in non-motorized modes. After each trip, the $PM_{2.5}$ readings were checked for errors. Resurveys had to be done for six trips. A master sheet was developed after linking mode-wise DT data with its corresponding GPS, temperature and relative humidity data.

2.5 Field Checks for DT Calibration

Dust Track instrument's conversion process of light intensity to mass concentration of particles depends on various factors like the size distribution, refractive index, shape and density of the particle as well as the absorbed humidity (DUSTTRAK™, 2008). Studies show that DT instruments have good precision; however, they record higher concentrations in comparison to the established reference gravimetric method. Thus, calibration is required (Huang, 2007; Joshua et. al, 2011; Kim et al., 2004.). The "Dust Track TM 8532" instruments are factory calibrated for Arizona Test Dust (ISO 12103-1), so a secondary calibration would enhance accuracy for Ahmedabad road dust conditions.

During each phase of the study, the DT instruments were calibrated by placing them together with the Gravimetric Samplers and conducting field checks at bus stations for 8 hours and 24-hour period. The correction factor (obtained by dividing the DT reading with the Gravimetric readings) showed slight variations (1 per cent- 4 per cent) for the two instruments. The average calibration factors (1.19 for instrument 1 and 1.25 for instrument 2) were applied to the readings of the corresponding DT.

2.6 Data Processing and Analysis

The data from DT, Temp-RH logger and GPS instruments was downloaded and inspected after each round trip. Any error or missing information was highlighted in the data. Repeat surveys had to be carried out in the few instances where instrument errors were detected. A detailed master sheet was prepared by trip-wise information showing exposure levels while commuting in all the nine modes and while waiting for public transport at the bus stops. The mastersheet included fields showing details of travel mode, date, time, peak, $PM_{2.5}$ recorded, $PM_{2.5}$ corrected, speeds, RH-Temp, segment and junction name. Even though the absolute values of $PM_{2.5}$ have been defined, focus was on comparing values among different modes.

Descriptive statistics were used for comparative analysis. Mean and standard deviation values have been used to describe the variation in $PM_{2.5}$ concentration levels. The findings are mostly represented graphically as "box plot" to bring out the simultaneous comparison and data variation. It shows the lowest and the highest recorded $PM_{2.5}$ values besides the first and the third quartile. $PM_{2.5}$ concentration levels are compared in terms of M and SD, wherein M represents the mean $PM_{2.5}$ concentration level and SD represents the standard deviation of the value. Statistical significance was established using the f-test and the t-test.

3. DISCUSSION OF RESULTS

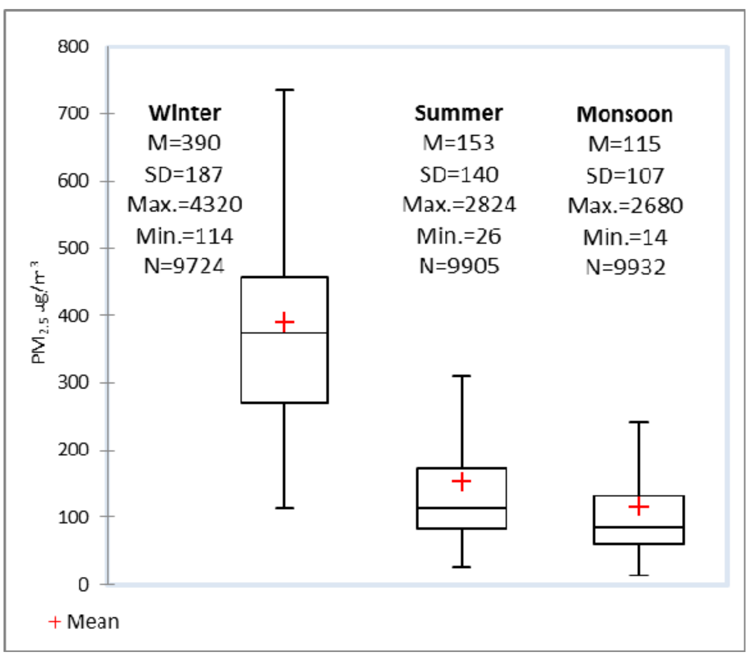
3.1 Seasonal Variation

$PM_{2.5}$ concentration levels were found to decrease from the winter (December-January) to the monsoon period (June-July). There was a marked reduction of 61 per cent for in-vehicle mean concentrations from winter to summer (April-May) (M=390 µg/m3, SD=187 in winter and M=153 µg/m3, SD=140 in summer) and then again a reduction of 25 per cent from summer to monsoon (M=115 µg/m3, SD=107) in non-AC modes (Figure 2). Statistical results using f and t-tests showed significant differences in the mean $PM_{2.5}$ levels between winter and summer (t-test, p=0) and between summer and monsoon (t-test, p < 0.00001) at the 95 per cent significance.

The trend was similar for bus stations, where we observed reduction of 34 per cent from winter to summer (M=267 µg/m3, SD=132 in winter; M=175 µg/m3, SD=162 in summer) and 32 per cent from summer to monsoon (M=119 µg/m3, SD= 92 in monsoon). Seasonal variation in $PM_{2.5}$ levels suggests meteorological impacts like reduced ventilation coefficient (determined as a function of average mixing height and average wind speed) during winter as compared to summer and monsoon. Low mixing heights are observed in India during the winter and monsoon, however stronger wind speeds and rains help to reduce ground level pollutant concentration in monsoon (Krishnan & Kunhikrishnan, 2004; Iyer & Raj).

Correlation results of in-vehicle $PM_{2.5}$ concentration with temperature and relative humidity showed a weak negative correlation with temperature (-0.332, P< 0.0001, R2=0.11) and a weak positive correlation with relative humidity (0.47, P<0.0001, R2=0.22). Temperature and RH gave a strong negative correlation (-0.94, P<0.0001, R2=0.88) with each other. Further research would be required to establish the meteorological impact on in-vehicle exposure.

Figure 2. Box plot representing commuter's exposure to $PM_{2.5}$ during winter, summer and monsoon trips in non-AC modes. (*The seasonal results include one-day trips conducted in each of the seven Non-AC modes (including 2 peaks and 1 off-peak hour trip/day).



3.2 Exposure to PM2.5 in Different Modes

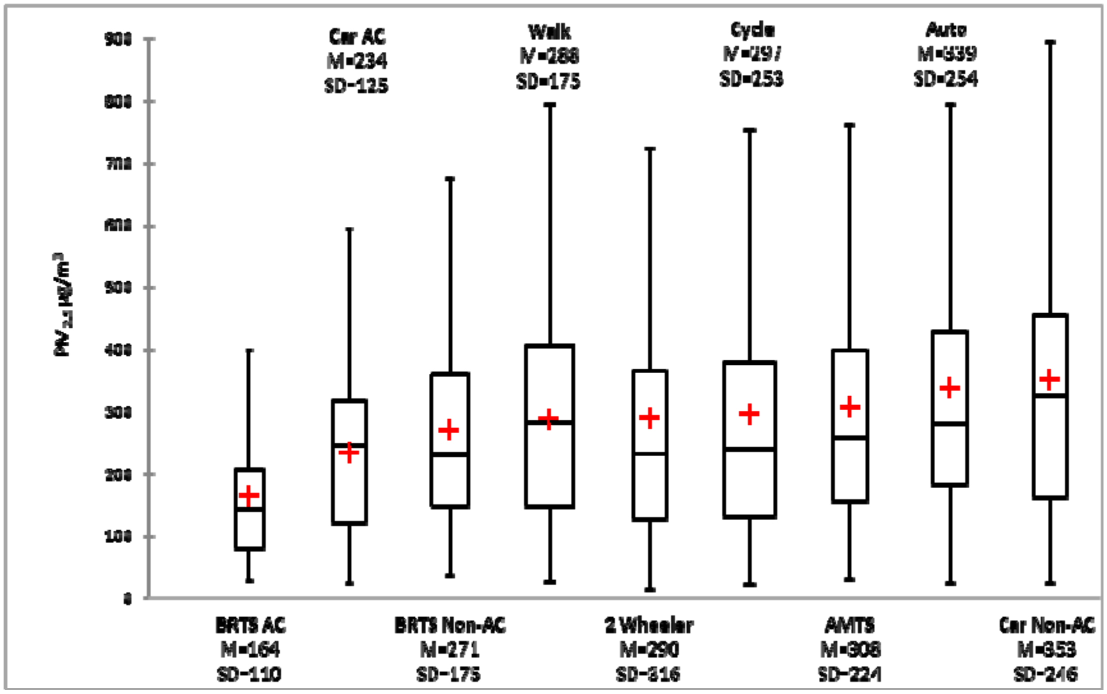
The in-vehicle concentration levels varied significantly between different modes. However, the pattern remained almost similar during each season as well as most of the trips. The $PM_{2.5}$ readings observed for all trips during December 2011 to July 2012 is summed up in table 1 and represented as box-plot diagrams in figure 3. The first (25^{th} percentile) and third quartile (75th percentile) of the concentrations are represented as the lower and upper parts of the box. The inter-quartile range as well as the outliers were minimum in AC BRTS buses followed by AC-cars and non-AC BRTS buses. While the median value and the inter-quartile range of open modes like walk, cycle and two-wheeler remained similar to non-AC BRTS, the numbers of outliers were very high in the open modes. Except BRTS (AC and non-AC) and AC-cars, all the other modes had a high number of outliers reaching beyond 2000 µg/m3. This shows strong influence of ambient and other factors (self-pollution etc.) for in-vehicle exposure. Summer and monsoon trips showed a similar sequence of mean exposure levels -AC BRTS (least) followed by AC car, walk, BRTS, cycle, two-wheeler, city-bus, non-AC car and then three-wheeler with highest levels. Winter sequence varied slightly with non-AC BRTS (M=325, SD=169) having a lower mean than walk (M=347, SD=150) and three-wheelers (M= 385, SD=248) slightly lower than non-AC car (M=414, SD=242).

Table 1. Descriptive statistics for all in-vehicle $PM_{2.5}$ exposures

Mode	Sea-son	Mean (µg/m^3)	Std. Error	Median (µg/m^3)	Mode (µg/m^3)	Std. D. (µg/m^3)	Range (µg/m^3)	Min. (µg/m^3)	Max. (µg/m^3)	Count
Closed/ Partially open modes										
BRTS Non-AC	W	325	2.0	264.4	236.8	168.7	1289	103.2	1392	6944
	S	139	2.4	117.6	92	75.7	616	51.2	667.2	974
	M	109	2.1	81.6	67.2	82.2	661	36.8	697.6	1535
AMTS	W	367	2.8	310.4	256.8	228.2	3587	84.8	3672	6733
	S	168	3.0	138.4	92.8	107.6	962	30.4	992	1294
	M	122	2.1	99.2	63.2	71.1	752	38.4	790.4	1174
Car Non-AC	W	414	3.1	383.2	432	242.1	2539	44.8	2584	6036
	S	180	4.2	134.4	104.8	135.2	938	29.6	968	1038
	M	123	3.4	99.2	93.6	99.2	1031	24.8	1056	846
Auto	W	385	2.9	328	260	247.8	4219	100.8	4320	7083
	S	206	7.1	140	76.8	229.9	2770	53.6	2824	1038
	M	134	4.9	92	70.4	148.3	1968	24	1992	919
Open modes										
2 W	W	359	4.7	300	317.6	346.8	7149	75.2	7224	5557
	S	165	4.6	126.4	96	139.8	1454	25.6	1480	939
	M	114	3.4	82.4	34.4	129.7	2666	14.4	2680	1485
NMT	W	347	1.3	315.2	288	214.4	5217	39.2	5256	27183
	S	132	1.9	100.8	91.2	127.9	2794	30.4	2824	4617
	M	110	1.7	78.4	52	104.6	1449	23.2	1472	3968
Air-conditioned modes										
CAR AC	W	292	1.3	280.8	274.4	95.0	1451	100.8	1552	5093
	S	116	2.0	93.6	89.6	61.5	337	24	360.8	920
	M	83	1.9	68	60	66.0	643	29.6	672.8	1202
BRTS AC	W	226	1.9	193.6	188.8	104.7	503	72	575.2	3124
	S	100	1.3	90.4	84	41.5	225	33.6	258.4	978
	M	67	0.7	64	43.2	27.4	384	28.8	412.8	1347

W=winter, S=summer, M=monsoon

Figure 3. In-vehicle $PM_{2.5}$ exposure pattern for all three seasons combined.



AC BRTS buses had lower exposure to $PM_{2.5}$ in comparison to other vehicles in any given season ($P<0.00001$). The mean $PM_{2.5}$ levels inside the AC BRTS bus (M=164 μg/m3, SD=110) was about 76 per cent lower than the mean exposure in all other modes combined ((M=289 μg/m3, SD=224). It was 57 per cent, 49 per cent and 67 per cent reduction in mean $PM_{2.5}$ levels against all other modes during winter, summer and monsoon respectively. Statistical results using t-tests show significant difference in the mean $PM_{2.5}$ levels between AC BRTS buses and all the other modes (t-test, P=0) at 95 per cent significance .

Amongst the non-AC vehicles, BRTS travelers were exposed to lower $PM_{2.5}$ concentrations. A comparison with the cumulative readings of all non-AC modes shows about 12 per cent reduction for non-AC BRTS commuters during both winter and summer and about 6 per cent reduction during monsoon (mode-wise reduction ranges from 19 per cent in the autos, 27 per cent in non-AC car and 13 per cent in AMTS during winter; 49 per cent in the autos, 30 per cent in non-AC cars and 21 per cent in AMTS during summer; 22 per cent in the autos to 12 per cent in non-AC cars and AMTS during monsoon). Statistical results using t-test show that, except NMT modes (walk and cycle) during summer and monsoon and two-wheelers during monsoon, all other modes have significantly higher exposure levels ($P<0.00001$) as compared to non-AC BRTS buses). The following reasons may explain low exposure in non-AC BRTS buses:

Segregation
BRTS plies in a 7.5-meter wide corridor in the center of the road defined with plantations in many areas.

Self-pollution
BRTS buses have Euro III and IV compliant engines

Height of Exposure
BRTS buses have 900 mm floor height

The modes can be broadly grouped as “Open” and “Closed” with AC/non-AC and segregated/mixed lane traffic option. Comparative results show distinct character for closed modes moving in mixed traffic lane. For e.g., AMTS buses moving in mixed traffic experience lower exposure than non-AC cars and three-wheelers probably due to the exposure height and air dispersal (number of windows). Non-AC cars and three-wheelers observed higher levels of $PM_{2.5}$ than most of the modes. It implies that factors like window openings, vehicle volume and exposure height from the ground have significant influence over the concentration levels.

Open modes like two-wheelers, walk and cycle observed a similar exposure pattern marked by sudden and frequent peaks of $PM_{2.5}$. Though air dispersion is quicker in open modes, spot exposure is sometimes higher due to localized pollution sources (tail pipe emissions from surrounding vehicles, road construction etc.). Pedestrians and bicyclists use footpaths and side lanes of the carriageway. As these are not in line with the tail pipes direction of vehicles, the concentration levels are relatively lower. Placing bicycle lanes and utility lanes (parking) appear to lower $PM_{2.5}$ exposure levels for commuters. It was observed that closed modes with air conditioning and segregation have reduced exposure levels.

3.3 PM2.5 Exposure Before and After BRTS Impementation

Systems from around the world have demonstrated the impact of BRTS on travel. A further benefit of the reduction in travel times is the reduction in exposure to $PM_{2.5.}$ Savings in travel time established through the BRTS in Ahmedbad result in lower $PM_{2.5}$ counts. On average, an AMTS bus travels 18 km/hr, bringing the average travel time to approximately 18 minutes per trip. With a modal shift of 50 per cent AMTS users shifting to BRTS, a significant decrease in average travel time to 13 minutes can indicate a significant reduction in the time exposed to $PM_{2.5}$. The lower $PM_{2.5}$ exposure associated with BRTS (as shown in Table 1) means shifting from any mode to an air-conditioned service will have considerable effects on the exposure levels. Table 2 shows a simple calculation conducted to estimate the percentage variation in exposure levels. The calculation uses mode share and per capita trip rate data to estimate the number of users and level of exposure based on their mode. This illustrates the before-BRTS scenario. Post-implementation of the BRTS, a similar calculation using mode shift data was used to show the number of users now being exposed to lower levels of $PM_{2.5}$. As a result, the variations between the before and after BRTS current scenario (based on modal shift) is 0.30 per cent (winter), 0.24 per cent (summer), and 0.14 per cent (monsoon). Ideally, the methodology should use travel data collected from the same corridor as the $PM_{2.5}$ count data, to establish more accurate results. In this case, the calculation is used to indicate a variation in pre and post implementation of the BRTS and to indicate the need for further assessment for more accuracy. The travel time savings of over 25,000 hours also suggests another potentially beneficial method to limit the exposure to fine particulate matter. This assessment demonstrates that BRT systems can potentially be a system that significantly lowers exposure levels for. A deeper assessment of exposure and concentration data could strengthen the case for BRT systems as a way to manage negative externalities associated with daily travel. Studies suggest that the most significant benefits are usually from the reduction in airborne fine particulate matter or $PM_{2.5}$. Additionally, with the health benefits assocaited with reduced exposure and multiplied by the vulnerable user groups there is strong potential for input into policy mandates. A scale-up strategy for BRTS ridership could significantly multiply the health benefits attained from lower exposure, benefitting users and others affected.

Table 2. Estimate the percentage variation in exposure levels

Modes	Season	Travel Time (mins)	$PM_{2.5}$ Count	Exposure Level	Modal Shift (per cent)	Travel Time Savings (mins)	$PM_{2.5}$ Count	Exposure Level
2W	W	41580000	5557	2.311E+11	14	217239.8	3124	2.30367E+11
	S		939	3.904E+10			974	39023406825
	M		1485	6.175E+10			1535	61713170932
IPT	W	10692000	7083	7.573E+10	30	465513.8	3124	73438843817
	S		1038	1.11E+10			974	11002611746
	M		919	9.826E+09			1535	10054367177
Car	W	3564000	5093	1.815E+10	2	31034.26	3124	18068792259
	S		920	3.279E+09			974	3276662461
	M		1202	4.284E+09			1535	4289175611
AMTS	W	21780000	6733	1.466E+11	50	775856.4	3124	1.41813E+11
	S		1294	2.818E+10			974	27544617770
	M		1174	2.557E+10			1535	25495582611
NMT	W	209088000	27183	5.684E+12	4	62068.51	3124	5.67329E+12
	S		4617	9.654E+11			974	9.63629E+11
	M		3968	8.297E+11			1535	8.28217E+11

3.4 Exposure Variation while Walking on Arterial and Internal Roads

As an extension to the survey, variation in $PM_{2.5}$ concentration was observed while walking on the main and internal streets. Results showed a reduction of 35 per cent-40 per cent in the mean levels monitored on the internal streets (M=91, SD=36) as compared to the arterial road (M=137, SD= 91). The peaks were frequent on the main road with elevated levels near the junctions mainly contributed by the vehicle emission due to the waiting traffic.

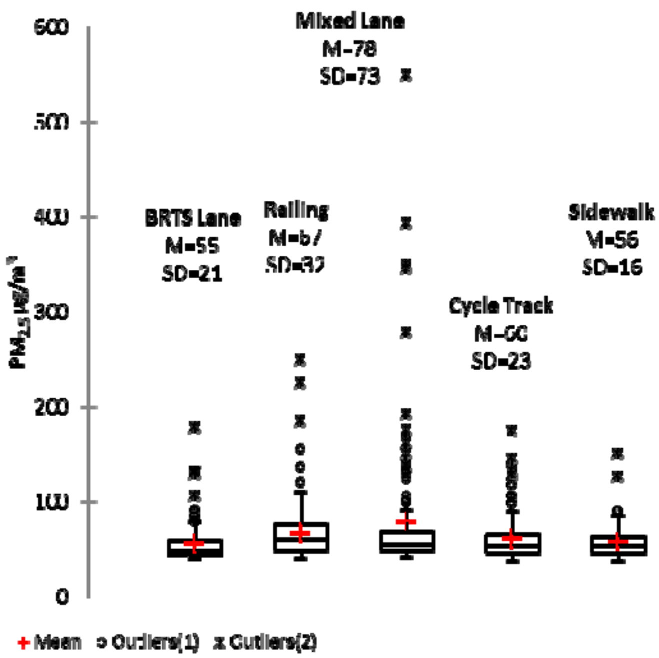
The results draw attention to factors like segregation, ventilation, enclosure and height of exposure. Though these form only a part of the large spectrum of variables that influence $PM_{2.5}$ concentrations, it helps to evaluate segregation and prioritization of public transport from the planning perspective.

3.5 Exposure Variation across Road Cross Section and with Altitude (in the Ambient Environment)

A typical 40 m cross section of the BRTS corridor includes a centrally segregated lane 7.5 m wide with three lanes of mixed traffic adjacent to it and NMT facilities at the edge. Monitoring across the road cross-section helped to observe the exposure variations at different points like the footpath, cycle track (where available), mixed lane, railing/ edge of the BRTS lane and the center of the BRTS lane. The $PM_{2.5}$ concentration levels were lowest on the footpath and increased as one moved into the mixed corridor. In a few cases, maximum level was observed at the right side of the mixed corridor, probably due to the presence of vehicle tail-pipes towards that side. The levels again came down in the BRTS corridor. A significant difference (t-test, p=0.002) was observed with about 30 per cent reduction in the mean $PM_{2.5}$ exposure inside the segregated BRTS lane as compared to the mixed lane (figure 4). This establishes the positive impact of segregation in case of BRTS.

In a follow-up survey to observe variation with height, recordings were done for 20-minute periods at three points closest to the ground at 300 mm, 900 mm and 1800 mm. Mean $PM_{2.5}$ concentrations were found to increase by 44 per cent near the ground level as compared to the reading at 1800mm from the ground - Height=300 mm (M=71, SD=24); Height=~900 mm (M=56, SD=19); Height=~1800 mm (M=49, SD=15). Proximity to the ground elevates exposure levels probably due to direct tail pipe emissions and re-suspension of road dust. This is significant as children with lower height of inhalation get more frequently exposed to elevated $PM_{2.5}$ concentration as compared to the adults.

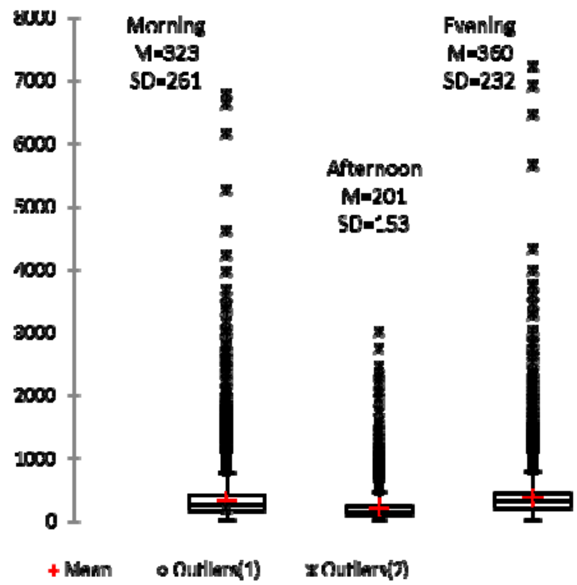
Figure 4. Variation of $PM_{2.5}$ exposure across the road, monitored at ~900 mm on 18 April 2012.



3.6 Exposure Variation during the Day

Diurnal assessment of the $PM_{2.5}$ exposure pattern shows low levels during the afternoon trips (1:30 PM- 4:00 PM) and elevated levels during the evening peak hour trips (6:30 PM-9:30 PM). A similar pattern was observed in all seasons for in-vehicle as well as bus station monitoring. The diurnal variation pattern was analyzed separately for the Non-AC and the AC Modes. The mean $PM_{2.5}$ levels during the evening non-AC trips were observed to be 44 per cent higher than the afternoon levels for all non-AC trips combined (Figure 5). The morning and evening variation ranged from 5 per cent in winter to about 34 per cent in summer and monsoon. Elevated $PM_{2.5}$ concentrations during the evening may be attributed to meteorological conditions (lower mixing height determined by various factors like temperature, relative humidity, wind speed, cloud cover, etc.) and also urban factors like traffic conditions. Evenings observed a heavy traffic flow with work and social trips occurring in the same period. In addition, the evening peak extends over a longer duration than the morning peak. There is lower diurnal variation in terms of mean $PM_{2.5}$ levels of AC modes during morning (M=185, SD=107); afternoon (M=148, SD=78) and evening (M=256, SD=138). Further research would be required to establish the exact reason for the diurnal $PM_{2.5}$ variation.

Figure 5. $PM_{2.5}$ diurnal variation in all the Non-AC in-vehicle trips (with outliers).



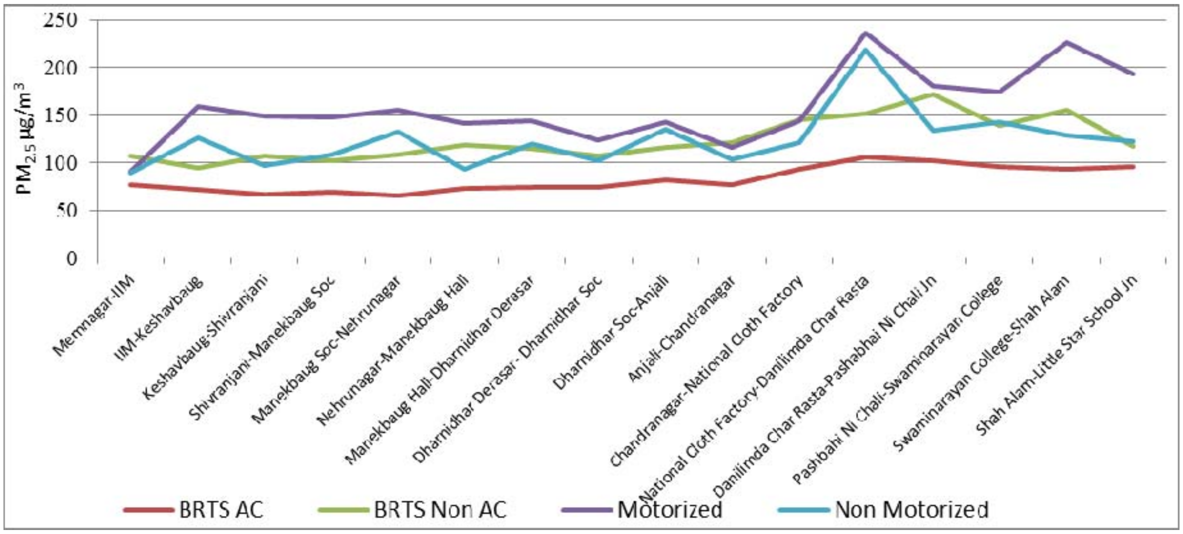
3.7 Variation with Location

In terms of location, few stretches in the eastern part of the corridor showed a consistent increase in $PM_{2.5}$ exposure levels. It includes the stretch from the *National Cloth Factory to Shah Alam*, which is industrial and mixed land-use development with informal settlements. In addition, there is heavy movement of freight vehicles like trucks on that corridor. Elevated readings were observed in this part during most of the in-vehicle trips. Ambient environment and heavy vehicle traffic movement appears to have a high influence on the in-vehicle $PM_{2.5}$ exposure levels. The western part of the corridor, *IIM* to *Keshavbagh,* showed elevated levels, especially in the evening trips for all the closed mixed traffic modes (non-AC Car, three-wheeler, two-wheeler), except non-AC BRTS. This may be due to traffic congestion at the *Keshavbagh* junction.

Stretches mainly in the western corridor, like *Keshavbagh to Shivranjani*, *Nehrunagar to Manekbaug hall*, *Dharnidhar Derasar- Dharnidhar Society and Anjali to Chandranagar* observed lower levels in almost all the modes. These are mainly residential areas with mixed-use development along the road.

The mean $PM_{2.5}$ levels were 17 per cent lower in the western segments of the corridor for all modes which increased to 23 per cent in AC BRTS buses (AC BRTS - West: M=149, SD= 110; East: M=193, SD= 105); (non-AC BRTS- West: M=260, SD=170; East: M=293, SD=182). Figure 6 shows location-wise variation in AC BRTS, non-AC BRTS, motorized and non-motorized modes along the corridor.

Figure 6. In-vehicle exposure variation for all modes - segment wise (cumulative results of April to July 2012)



3.8 BRT Bus Stations

A 20-minute dust tracking survey conducted at 16 BRTS stations during the three peak periods showed a similar pattern as in-vehicle exposure with respect to the seasonal and diurnal variation. The seasonal drop was 34 per cent from winter to summer and 32 per cent from summer to monsoon. The diurnal levels dropped by 38 per cent from morning (M=241 µg/m3, SD=139) to afternoon (M=150 µg/m3, SD=83) and then increased by about 80 per cent in the evening (M=268 µg/ m3, SD=181) from the noon levels. Overall, the $PM_{2.5}$ levels in the western side BRT stations were 22 per cent lower than the eastern side stations ($P<0.001$). In many cases, BRTS stations nearer to the junction with traffic congestion recorded higher levels of concentrations (for example *Andhjan Mandal* and *Shivranjani* BRTS Stations which are less than 100 meters away from the junction). Further research is required to analyze the role of orientation, design and other factors in influencing the exposure levels inside the stations as established from literature review (Moore, Figliozzi, & Monsere, 2012).

4. CONCLUSIONS

The study suggests that mode type, location, seasonal as well as temporal variations due to meteorological conditions impacts the exposure of commuters to $PM_{2.5}$. It was observed that closed modes with air conditioning and segregation have reduced exposure levels than open modes like two-wheeler, walk and cycle. Partially closed modes in mixed traffic lanes such as non-AC city bus, three-wheeler and non-AC car experience maximum $PM_{2.5}$ pollution. The survey results show, AC BRTS commuters experienced minimum $PM_{2.5}$ concentration levels irrespective of season and time of the day. There is about 25 per cent reduction in mean $PM_{2.5}$ levels of AC BRTS as compared to the AC car users and about 76 per cent reduction with respect to other non-AC modes. Movement in segregated lanes, height and its volume seem to play a significant role in minimizing the concentration levels in BRTS buses. The reduction of travel time by around 25,000 hours suggests that the time exposed to higher $PM_{2.5}$ counts can be minimised through BRTS, while ensuring better health benefits. It can be concluded that policy decisions for maximizing the BRTS fleet of AC buses will significantly reduce commuter's exposure to $PM_{2.5}$. There is an increase in cities which are developing BRTS, thus similar studies will be useful in verifying the particle pollution exposure results.

The results showed that $PM_{2.5}$ concentrations varied significantly over the year with lowest levels during the monsoon and maximum during winters. The mean levels reduced by 61 per cent from winter to summer and then again by 25 per cent from summer to monsoon. Diurnal assessment of $PM_{2.5}$ levels across modes indicated lowest levels in the afternoon and highest during the evening peak hours. This is relevant for commuters, especially in the sensitive group for avoiding travel during peak hours, as it increases their chances of exposure to elevated $PM_{2.5}$ levels. Also, higher $PM_{2.5}$ levels as one gets closer to the ground is an important observation from the design and planning perspective. Children with lower inhalation height are likely to be exposed frequently to elevated $PM_{2.5}$ levels. For pedestrians and cyclists, commuting on internal streets (with lower traffic and source pollution) rather than a busy arterial road can be favorable from the health perspective. The findings also suggest that cyclists and walkers commuting on un-segregated lanes for long hours pose increased vulnerability to elevated exposure levels.

The study provides a platform to influence policy decisions for promoting segregated public transport as well as non-motorized transport considering the health perspective. It can be scaled up to promote awareness about real time exposure to pollutants, thus creating awareness for healthier modes of transport.

ACKNOWLEDGEMENTS

We thank Centre of Excellence-Urban Transport, CEPT University staff for participating in the field measurements and data analysis and EMBARQ India for providing the Dust Track Instruments

REFERENCES

Adams, HS, MJ Nieuwenhuijsen, RN Colvile, MA McMullen, and P Khandelwal. Fine particle ($PM_{2.5}$) personal exposure levels in transport microenvironments, London, UK. The Science of The Total Environment, 2001: 279 (1-3), pp. 29-44.

Bell, ML, K Ebisu, and K Belanger. Ambient Air Pollution and Low Birth Weight in Connecticut and Massachusetts." Environmental Health Perspectives, 2007: 115 (7), pp. 1118-1125.

Brook, RD, et al. Particulate Matter Air Pollution and Cardiovascular Disease: An update to the scientific statement from the American Heart Association. American Heart Association, 2010: 121 (21), pp. 2331-78.

CoE, Urban Transport- CEPT University and Ahmedabad Urban Development Authority (AUDA), Integrated Molility Plan for Greater Ahmedabad Region. Ahmedabad, 2013.

Dominici, F, et al. Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases. Journal of the American Medical Association, 2006: 295 (10), pp. 1127-1134.

DUSTTRAK™ II Aerosol Monitor Theory of Operation. TSI Incorporated, 2008.

Hill, LB, NJ Zimmerman, and J Gooch. A Multi-City Investigation of the Effectiveness of Retrofit Emissions Controls in Reducing Exposures to Particulate Matter in School Buses. 2005.

Huang, Cheng Hsiung. Field Comparison of Real-Time $PM_{2.5}$ Readings from a Beta Gauge Monitor and a Light Scattering Method. Aerosol and Air Quality Research, vol. 7, No. 2, 2007, pp. 239-250.

Iyer, U.S., and P.E. Raj. Ventilation coefficient trends in the recent decades over four major Indian metropolitan cities. www.ias.ac.in/jess/forthcoming/JESS-D-12-00099.pdf (Accessed Jan. 20, 2013).

Joshua S. Apte, Thomas W. Kirchstetter b, Alexander H. Reich c, Shyam J. Deshpande c,. Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. Atmospheric Environment 45, 2011, pp. 4470 - 4480.

Kaur, S, MJ Nieuwenhuijsen, and RN Colvilea. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmospheric Environment 41, 2007, pp. 4781-4810.

Kim JY, Magari SR, Herrick RF, Smith TJ, Christiani DC. Comparison of fine particle measurements from a direct-reading instrument and a gravimetric sampling method. Journal of Occupational and Environmental Hygiene, 2004 Nov., pp. 707-15.

Krishnan, P., and P.K. Kunhikrishnan. Temporal variations of ventilation coefficient at a tropical Indian station using UHF wind profiler. Current Science, 86, 2004, pp. 447-451.

Laden, F, J Schwartz, FE Speizer, and DW Dockery. Reduction in fine particulate air pollution and morality: extended follow-up of the Harvard Six Cities study. American Journal of Respiratory and Critical Care Medicine, 2006: 173, pp. 667-643.

Moore, Adam, Miguel Figliozzi, and Christopher M. Monsere. Air Quality at Bus Stops: Empirical Analysis of Exposure to Particulate Matter at Bus Stop Shelters. In Transportation Research Record: Journal of the Transportation Research Board, No. 2270, Transportation Research Board of the National Academies, Washington DC, 2012, pp. 76-78.

Pope III, C. Arden, and Douglas W. Dockery. Health Effects of Fine Particulate Air Pollution: Lines that Connect. Air & Waste Management Association 56, 2006, pp. 709–742.

Sabapathy, Ashwin, K.V. Santhosh Ragavan, and Sumeet Saksena. An Assessment of Two-Wheeler CO and PM10 Exposures Along Arterial Main Roads in Bangalore City, India. The Open Atmospheric Science Journal (Suppl 1: M3), 2012, pp. 71-77.

Wang, X.R, and H.O Gao. Analysis of Travelers' Exposure to Fine Particle (PM 2.5) Mass and Number Concentrations in Urban Transportation Environments - a Case Study in New York City. In Transportation Research Record: Journal of the Transportation Research Board, vol.16, issue 5, Research Board of the National Academies, Washington DC, 2011, pp. 384-391

Wohrnschimmel, H, et al. The impact of a Bus Rapid Transit system on commuters' exposure to Benzene, CO, $PM_{2.5}$ and PM10 in Mexico City. Atmospheric Environment, 2008: 42, pp. 8194–8203.