On-Road Pollution Exposure in Multiple Transport Micro-Environments: A Case Study of Tier 2 & Tier 3 Cities in India

Ranjana KUMARI [a], Kapil Kumar MEENA [b], Arkopal Kishore GOSWAMI [c]

[a,b,c] *Indian Institute of Technology Kharagpur, India, 721302*
[a] *E-mail: ranjanasingh086@gmail.com*
[b] *E-mail: kapilm.48@gmail.com*
[c] *E-mail: akgoswami@infra.iitkgp.ac.in*

Abstract: Air pollution poses a major threat to public health, particularly across India's rapidly expanding urban areas. This study examines how transportation modes influence commuters' exposure to major pollutants (NO_2, CO, PM_{10}, and $PM_{2.5}$) in Varanasi (a Tier 2 city) and Kharagpur (a Tier 3 city). Using a portable handheld device, data was collected during morning peak, midday, and evening peak hours on arterial and collector stretches while participants walked, rode a two-wheeler, or traveled by auto-rickshaw. Among these modes, auto-rickshaw commuters experienced the highest pollutant concentrations, with the evening peak hours exhibiting the maximum exposure. Additionally, CO concentrations for pedestrians were significantly higher on arterial stretches compared to collector roads. Pedestrians recorded the greatest inhaled dose of pollutants overall. These findings underscore the need for targeted interventions, guiding both commuters and policymakers toward minimizing pollutant exposure and mitigating the associated health risks in congested urban environments.

Keywords: air pollution exposure, travel modes, active modes, transportation planning

1. INTRODUCTION

The surge in urbanization and expanding transportation has led to a decline in air quality, severely impacting global health (Boston 2019). In 2021, 7 million lives were lost worldwide due to ambient air pollution, with India witnessing an estimated 1.7 million air pollution-related deaths in 2020, constituting 18% of the country's total mortality (Pandey 2021). India ranked as the third most polluted country globally in 2021, with an annual average $PM_{2.5}$ concentration of 51.29 $\mu g/m^3$(IQAir 2020). Vehicular pollution has been identified as a primary contributor to urban pollution in a study by (R. a. Goel 2015). Commuters, especially pedestrians and cyclists, are disproportionately affected due to their proximity to traffic and elevated respiration rates (Meena & Goswami, 2024). Notably, studies have shown that approximately 32.7% of daily pollution exposure occurs during just 8% of total travel time, underscoring the intense, short-duration exposure associated with commuting (Rivas 2017, Bauer 2018). Although several Indian studies have examined travel-related exposure to pollutants (see Table 1), significant gaps remain. Few explore exposure variation across pollutant types, street environments, travel modes, and time periods. More importantly, limited research has assessed inhaled dose—an indicator that combines pollutant concentration with ventilation rates to reflect actual physiological exposure. While earlier studies—such as (Manojkumar et al., 2021) in Vellore—have measured $PM_{2.5}$ exposure in Tier-3 cities, key methodological and contextual gaps persist. This study addresses those gaps through several distinct contributions. It investigates two cities—Varanasi (Tier-2) and Kharagpur (Tier-3)—capturing diverse urban forms, street layouts, and travel behaviors. It also includes real-time monitoring of multiple pollutants—PM_{10}, $PM_{2.5}$, NO_x, and CO—using GPS-enabled portable instruments to assess spatial exposure along predefined street segments. Most notably, it estimates inhaled doses across transport modes by integrating pollutant levels with mode-specific physical activity and ventilation rates. These enhancements provide a more comprehensive and health-relevant understanding of commuter exposure in rapidly growing but under-researched Indian cities. This study aims to analyze on-road pollution exposure and estimate inhaled doses across transport modes in Tier-2 and Tier-3 cities. Although it does not evaluate pollutant source contributions or emission characteristics, the findings offer actionable insights for commuters and policymakers—guiding more effective mitigation strategies for small and mid-sized urban centers in India.

Table 1- Past $PM_{2.5}$ exposure studies for transport micro-environments

Study	Location	Pollutant (µg/m3)	Car	Bus	Metro	Two-Wheeler	Auto-Rickshaw	Walking
(Apte 2011)	Delhi	$PM_{2.5}$	-	-	-	-	190	-
(Maji 2021)	Delhi	$PM_{2.5}$	149	113	72	266	-	259
(R. S. Goel 2015)	Delhi	$PM_{2.5}$	180	277	87	207	257	234
(S. S. Kolluru 2020)	Vijayawada - Guntur	$PM_{2.5}$	29	37	-	-	-	-
(Raj 2020)	Chennai	$PM_{2.5}$	-	225	-	251	-	-
(Swamy 2015)	Ahmedabad	$PM_{2.5}$	383	-	-	300	328	-
(S. S. Kolluru 2018)	Vijayawada	$PM_{2.5}$	85	75	-	-	-	-
(Manojkumar et al., 2021)	Vellore	$PM_{2.5}$	182	127	–	144	212	128

2. Study Area and Methodology

Two cities were selected as case study locations based on their distinct urban characteristics, levels of urbanization, and air quality concerns. Varanasi, a Tier-2 city in Uttar Pradesh and the cultural capital of India, faces high traffic congestion, narrow streets, and elevated $PM_{2.5}$ levels due to dense mixed-use development and limited non-motorized transport infrastructure. Kharagpur, a Tier-3 city in West Bengal, exhibits low to moderate congestion, lower population density, and more open urban form, offering a contrasting air quality and mobility profile. These cities are representative of the emerging urbanization pattern in India, where Tier 2 and Tier 3 cities are expected to experience rapid growth but remain underrepresented in pollution and transport research. Studying pollution exposure in these contexts is vital to ensuring equitable environmental and transport policy responses beyond India's mega-cities.

2.1 Data Collection, Instrument And Experimental Setup

The primary survey was done in both cities to comprehend the objective by collecting air quality data using a portable handheld air quality monitoring instrument. The study was conducted in the month of October - November, 2019. The individual's exposure to major pollutants, like NO_2, CO, PM_{10} and $PM_{2.5}$, while walking, using a two-wheeler, or travelling on an auto-rickshaw. The data is collected during morning peak hours, mid-day, and evening peak hours along 1.5 kms each of three arterial and three collector stretches in both the case study cities. The data was collected using the Aeroqual Series 500 – Portable Air Quality Monitor, containing NO_2, CO, PM_{10} and $PM_{2.5}$ sensors. The Series 500 air quality sensor enables accurate real-time surveying of common outdoor air pollutants, all in an ultra-portable handheld monitor. Sensors are housed within an interchangeable cart head that attaches to the monitor base. The head can be removed and replaced easily, allowing users to measure as many gases as they wish. Sensor heads feature active fan sampling, which ensures a representative sample is taken and increases measurement accuracy. For other features of the Series 500, readers are referred to the website1. Once switched on, the equipment records pollutant concentrations continuously at 1-minute intervals. Location ID can be used to tag measurements to a specific location which is helpful when sampling at several sites over the course of a day or week. The device was placed (see Figure 1) at a distance of 2-5 m. away from the carriageway at each of the selected locations. The sensor provides readings at one-minute intervals. The survey was conducted in Varanasi from October 31 - November 8, 2019, and in Kharagpur between October 14 - October 19, 2019. The data collection personnel carried the handheld monitors with them while they were either walking, or on the 2-wheeler, or using an auto-rickshaw. The distance traversed in all three cases was 1.5 km. Two of the monitors were clamped to the backpack straps that the personnel carried, while the third monitor was held in the hand. In addition to this, located at stationary locations, along different types of urban street categories, such as at mid-block, at intersection, and after intersection. In these cases, the monitors were mounted on tripods, alongside each other, and placed on the side of the streets, at a distance of 2.5 m from the street edge. This enabled them to simultaneously capture the concentrations of the four pollutants at each location. It is to be also noted here that, as a part of the larger experimental set up, along with this static pollutant concentration data, the researchers also captured the traffic data at these static locations by placing video cameras alongside the air quality monitors. However, this paper does not extensively present the analysis showing the correlation between traffic parameters and pollutant concentrations. Only aggregate-level traffic data is discussed. For greater detail, the authors refer readers to another publication (Ranjana Kumari 2022).

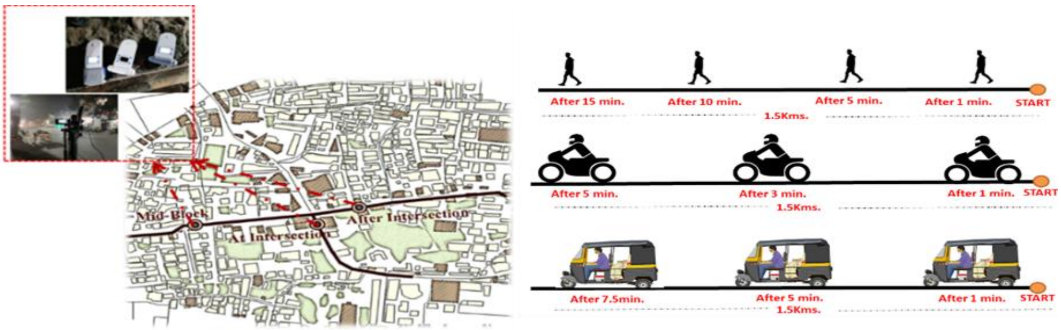


Figure 1- Experimental Setup

In total, 70 trips were completed in each of the cities, out of which 10 trips were completed by walking, 30 trips by auto-rickshaw and 30 trips were completed using motorized two-wheelers. Out of total trips, half of the trips were made on arterial stretch and half on collector stretch. Along each of the stretches, 14 trips were completed during the morning peak hour (8-10 am), seven trips during the mid-day period (2-3 pm) and 14 trips during the evening peak hour (5-7 pm). The average time taken to complete one round trip is 30 min, 10 min. & 15 min. for a walk, two-wheeler and auto-rickshaw, respectively (see Figure 2). In both tier 2 and tier 3 cities, the data has been extracted to get the total traffic volume count of different locations and to get the fleet mix of the traffic. The data Extraction has been done using two different algorithms: a) You look only once (YOLO) algorithm for detection and classification b) DEEPSORT for tracking and counting. Figure 2 shows the vehicular volume count of Varanasi and Kharagpur; the maximum traffic volume count has been recorded during the morning peak hour as compared with the mid-day and evening peak hours.

[1]https://www.aeroqual.com/products/s-series-portable-air-monitors/series-500-portable-air-pollution-monitor

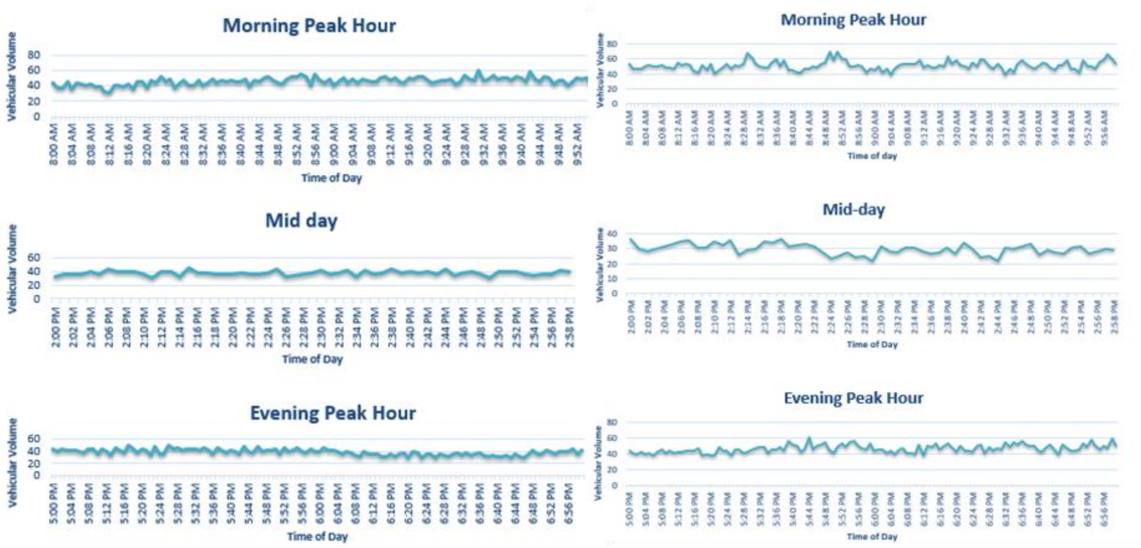


Figure 2- Variation in vehicular volume throughout the day: Varanasi (left) and Kharagpur (right)

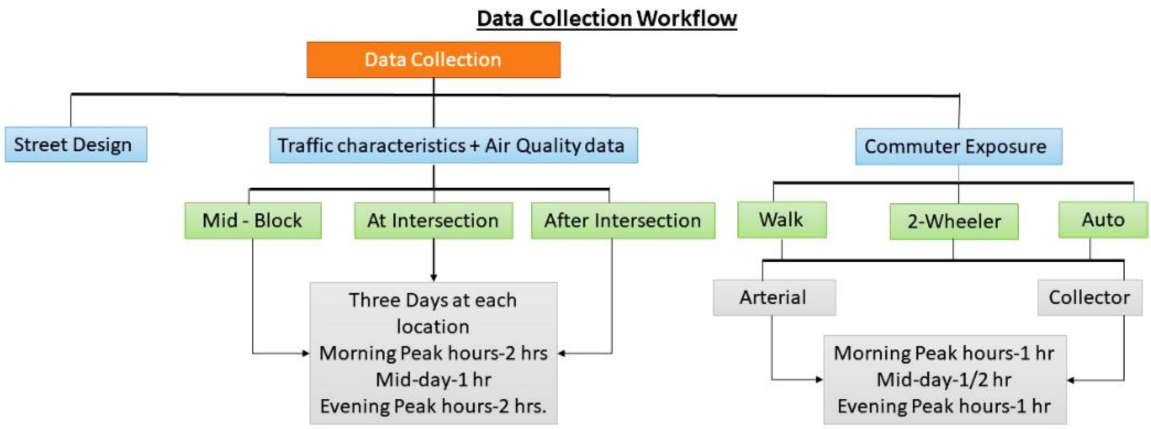


Figure 3- Data collection workflow

3 Results

Commuter exposure analysis has been done to analyze the effect of transportation modes on the amount of exposure to road users and to investigate the spatial and temporal variability in commuter's exposure to ground-level air pollution.

3.1 Descriptive Statistics

In Varanasi (Figure 4) the overall average concentration of CO, NO_2, and in (Figure 5) shows the PM_{10} and $PM_{2.5}$ varied from 0.82-9.76 *ppm*, 0.102-0.195 *ppm*, 0.237-0.939 *ppm* and 0.150-0.772 *ppm* respectively. While, in the case of tier 3 city, i.e., Kharagpur, the overall average concentration of CO varied from 1.06 - 4.43 *ppm* and the concentration of NO_2 varied from 0.03-0.2 *ppm*, While in the (Figure 5) PM_{10} and $PM_{2.5}$ varied from 0.002-0.008 *ppm*, and 0.001-0.004 *ppm* respectively.

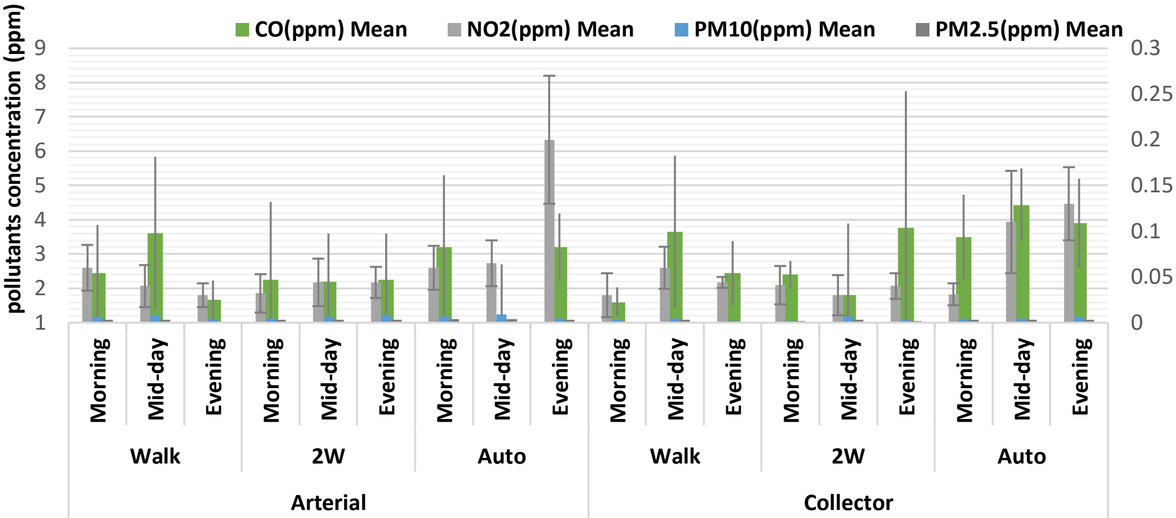


Figure 4- Descriptive statistics of pollutants concentration: Varanasi

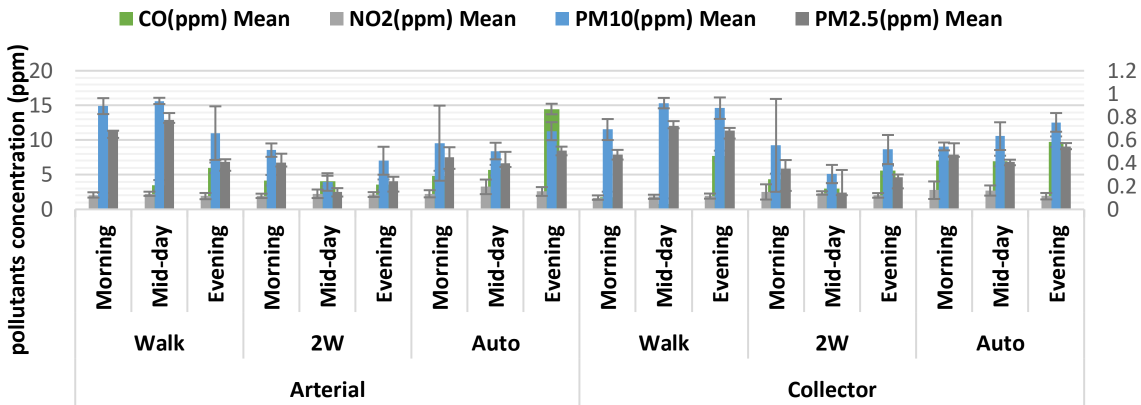


Figure 5- Descriptive statistics of pollutants concentration: Kharagpur

The results show that the levels of pollutant concentrations are markedly lower in Kharagpur when compared to Varanasi. The maximum concentration of pollutants has been recorded when auto-rickshaw is used as a mode of commuting in both cities. This could be attributed to the fact that the auto-rickshaws which ply in both the cities are of old models which have their engines inside the vehicle and use petrol and diesel as a fuel source. Also, exposure in an auto-rickshaw is higher pertaining to the design of the vehicle as its ventilation condition is open (Kaur 2005). Previous studies (R. a. Goel 2015, Chen 2010) also found that the concentration of pollutants was higher in the case of vehicles like auto-rickshaws and taxis, thus indicating that pollutant concentrations, especially of CO, are a result of in-vehicle accumulation. The minimum amount of pollutants concentration has been measured in the case of walking, and the same result has been found in a study done by (Huang 2012).

3.2 Cumulative Exposure of Commuters

The cumulative amount of exposure has been calculated for commuters when they are commuting for a time period using different modes of transportation. The maximum exposure of all the pollutants in both the cities has been recorded during evening peak hours. The Figure 6, 7 shows the cumulative exposure of CO pollutant at different times of the day when the walk is used as a mode of commuting along an arterial stretch in both cities. It is observed that in Varanasi a pedestrian while walking for 60 minutes, is exposed more in the morning as compared to the evening peak hours.

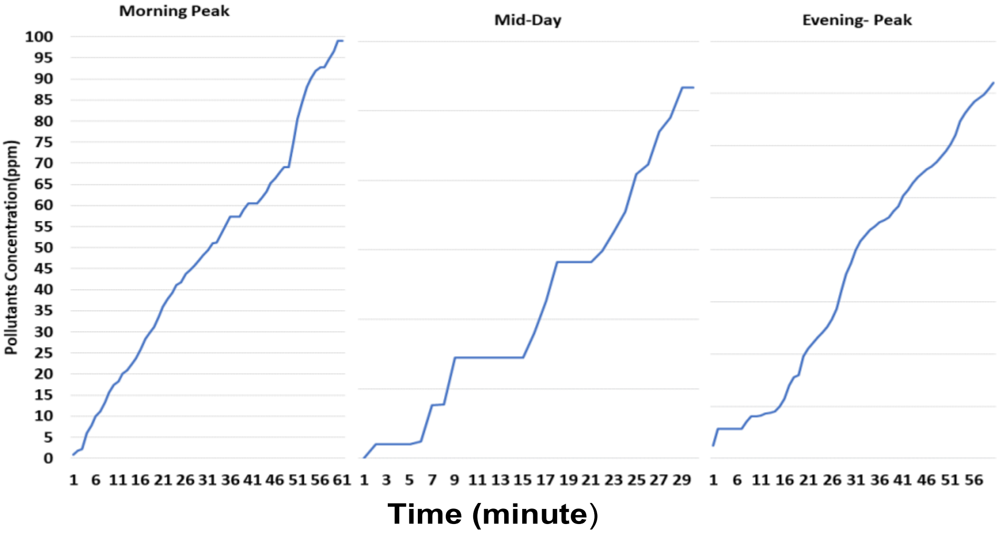


Figure 6- Cumulative CO exposure of pedestrians for a complete trip: Varanasi

In the case of Kharagpur however, the amount of exposure to CO is similar during both the peak hours. The study emphasizes the exposure in terms of time rather than distance, because for traversing a same distance, it is likely to take a commuter varying amounts of time, based on the travel mode and time of the day. As such, although the time taken to traverse the 1.5 km may be different, but from the cumulative exposure, one can estimate the average exposure per minute. As such, it can be seen that in Varanasi (see Figure 6) during the peak hours, a pedestrian is exposed to CO concentrations in the range of 1.5 - 1.9 *ppm* per minute, whereas during mid-day this exposure is around 3.9 *ppm* per minute. Similarly, in case of Kharagpur (see Figure 7), during morning peak hours, exposure to CO concentration is around 2.5 *ppm* per minute, while during mid-day it is on an average about 5.3 *ppm* per minute.

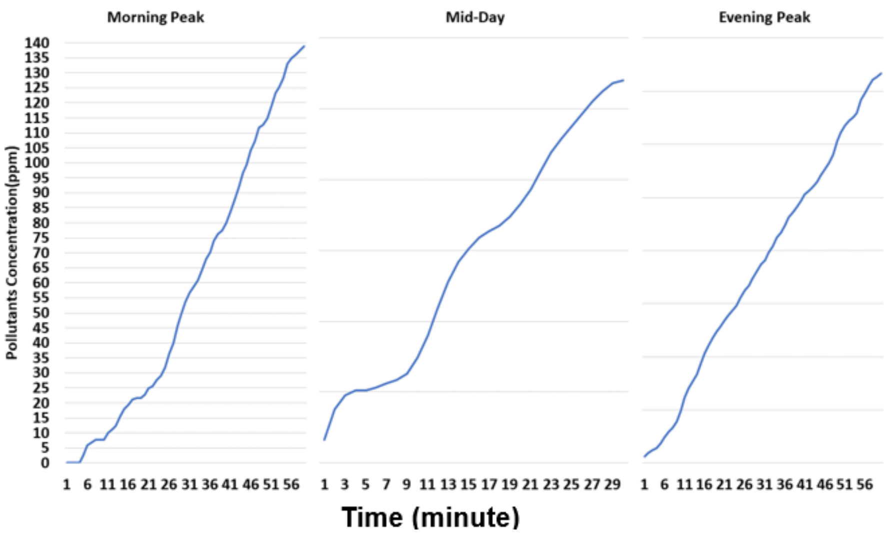
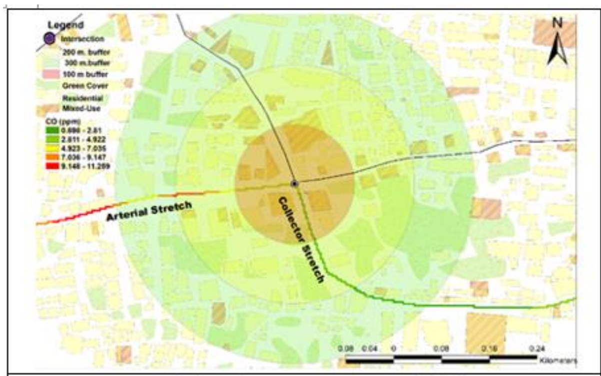


Figure 7- Cumulative CO exposure of pedestrians for a complete trip: Kharagpur

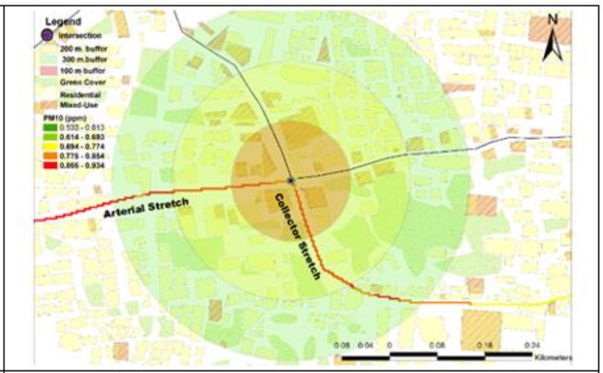
3.3 Pedestrian Exposure Mapping

The spatial mapping of selected pollutants, i.e., CO, NO_2, PM_{10} and $PM_{2.5}$ has been done to analyse the amount of exposure of pedestrians to different pollutants when they are walking along an arterial versus collector stretch in the Varanasi because of higher concentration as compared to Kharagpur. The exposure data has been collected using a personal monitoring device, and then they have combined with GPS locations to give them spatial recognition. Mapping of pollutants has been done using Arc GIS 10 software.

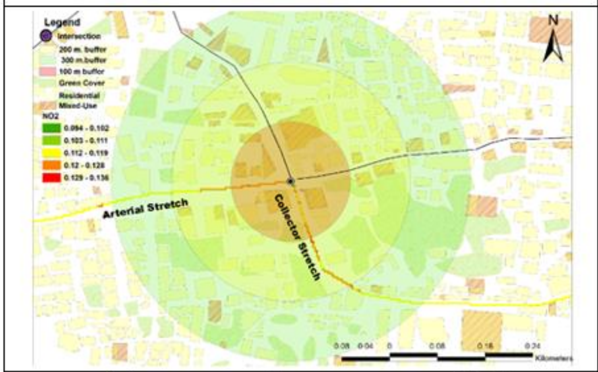
Figure 8 shows to what extent a pedestrian is exposed to a certain pollutant concentration and how it varies along an arterial versus a collector when one is closer to the intersection and while moving away from the intersection. As shown in Figure 8a, it has been found that the exposure is higher when people are walking along an arterial stretch as compared to that of a collector stretch. This is intuitive as the volume of vehicles on an arterial stretch is usually greater as compared to a collector stretch. Also, the movement of heavy vehicles on collector stretches is usually low as compared with arterial stretch. In the case of pollutants such as NO_2, PM_{10} and $PM_{2.5}$ (Figure 8b, Figure 8c, Figure 8d) very less difference has been seen in the level of exposure to pedestrians on both stretches.



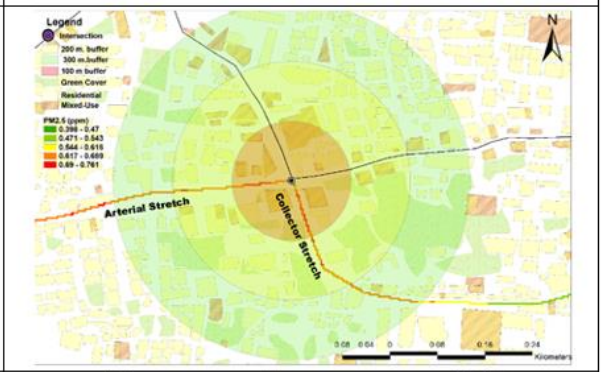
(a) Exposure map of CO



(b) Exposure map of NO_2



(c) Exposure map of PM_{10}



(d) Exposure map of $PM_{2.5}$

Figure 8- Exposure map of different pollutants

3.4 Inhaled Dose Estimation

Once the amount of pollutant concentrations that the commuters are exposed to was measured, the next step was to convert it into the dosage of pollutants being inhaled by the commuters. With the increase in the proximity to traffic, various transportation micro-environments can exhibit relatively higher concentration, which is sometimes aggravated by a high inhalation rate, especially in terms of active transportation like walking and cycling. The inhalation or intake of pollutant dose for the commuters has been calculated using Equation (1) given by (N Dirks 2012). In this, the actual dose of pollutants inhaled by the commuter for each of the mode has been calculated using the formula:

$$Dose\ (ppm * h) = [Pollutant](ppm) * Commute\ time\ (h) * Exercise\ factor \quad (1)$$

where the exercise factor was defined as the ratio of the minute ventilation factor for a particular mode to the resting rate experienced by those commuting via sedentary modes. For individuals traveling by auto-rickshaw and two-wheelers, a resting minute ventilation rate of 12 L per minute was assumed. Pedestrians were assumed to have a minute ventilation rate of 48 L per minute. Therefore, the exercise factor for two-wheelers and auto-rickshaws was taken as 1, while for pedestrians, it was taken as 4. The calculated inhaled dose for both the cities is shown in Table 2.

Table 2- Total inhaled dose of pollutant for commuters: Varanasi and Kharagpur

Stretch	Timings	Mode	Trip Averaged Concentrations (ppm)				Commute Time / round trip (hr.)	Exercise factor	Inhaled Dose (ppm)			
			CO	NO_2	PM_{10}	$PM_{2.5}$			CO	NO_2	PM_{10}	$PM_{2.5}$
			Varanasi / Kharagpur	Varanasi / Kharagpur	Varanasi / Kharagpur	Varanasi / Kharagpur			Varanasi / Kharagpur	Varanasi / Kharagpur	Varanasi / Kharagpur	Varanasi / Kharagpur
Arterial	Morning	Walk	1.6 / 1.7	0.118 / 0.045	0.885 / 0.007	0.662 / 0.003	0.5	4	3.2 / 3.4	0.23 / 0.09	1.77 / 0.014	1.324 / 0.006
		2-W	2.9 / 0.8	0.104 / 0.041	0.498 / 0.007	0.442 / 0.004	0.16	1	0.46 / 0.13	0.017 / 0.007	0.08 / 0.001	0.071 / 0.001
		Auto	7.3 / 2.1	0.237 / 0.072	0.506 / 0.006	0.447 / 0.003	0.25	1	1.82 / 0.53	0.059 / 0.018	0.127 / 0.002	0.112 / 0.001
	Mid-Day	Walk	3.4 / 1.6	0.135 / 0.025	0.939/ 0.004	0.772 / 0.001	0.5	4	6.8 / 3.2	0.27 / 0.05	1.878 / 0.008	1.544 / 0.002
		2-W	2.05 / 2.1	0.124 / 0.046	0.269 / 0.006	0.165 / 0.003	0.16	1	0.32 / 0.34	0.02 / 0.007	0.043 / 0.001	0.0236 / 0
		Auto	2.6 / 2.17	0.202 / 0.067	0.498 / 0.007	0.395 / 0.003	0.25	1	0.65 / 0.54	0.051 / 0.017	0.125 / 0.002	0.099 / 0.001
	Evening	Walk	6.2 / 3.6	0.108 / 0.049	0.662 / 0.004	0.372 / 0.001	0.5	4	12.4 / 7.2	0.216 / 0.098	1.324 / 0.008	0.744 / 0.002
		2-W	2.9 / 1.65	0.115 / 0.015	0.331 / 0.009	0.195 / 0.002	0.16	1	0.46 / 0.26	0.018 / 0.002	0.053 / 0.001	0.031 / 0
		Auto	15.38 / 3.6	0.187 / 0.2	0.656 / 0.005	0.482 / 0.003	0.25	1	3.84 / 0.9	0.047 / 0.05	0.164 / 0.001	0.121 / 0.001
Collector	Morning	Walk	2 / 3.2	0.101 / 0.036	0.713 / 0.002	0.489 / 0.001	0.5	4	4 / 6.4	0.202 / 0.072	1.426 / 0.004	0.978 / 0.002
		2-W	2.6 / 0.5	0.171 / 0.04	0.488 / 0.006	0.341 / 0.002	0.16	1	0.41 / 0.08	0.027 / 0.006	0.078 / 0.001	0.055 / 0
		Auto	2.4 / 1.8	0.121 / 0.061	0.487 / 0.005	0.424 / 0.003	0.25	1	0.6 / 0.45	0.03 / 0.015	0.122 / 0.001	0.106 / 0.001
	Mid-Day	Walk	0.82 / 2.5	0.109 / 0.044	0.92 / 0.001	0.722 / 0.001	0.5	4	1.64 / 5	0.218 / 0.088	1.84 / 0.002	1.444 / 0.002
		2-W	2.9 / 2.08	0.135 / 0.034	0.289 / 0.003	0.158 / 0.002	0.16	1	0.46 / 0.33	0.022 / 0.005	0.046 / 0	0.025 / 0
		Auto	6.5 / 4.2	0.173 / 0.089	0.658 / 0.005	0.407 / 0.003	0.25	1	1.62 / 1.05	0.043 / 0.022	0.165 / 0.001	0.102 / 0.001
	Evening	Walk	8.6 / 3.7	0.117 / 0.062	0.874 / 0.002	0.68 / 0.001	0.5	4	17.2 / 7.4	0.234 / 0.124	1.748 / 0.004	1.36 / 0.002
		2-W	2.8 / 2.35	0.129 / 0.045	0.366 / 0.003	0.198 / 0.001	0.16	1	0.44 / 0.38	0.021 / 0.007	0.059 / 0	0.032 / 0
		Auto	9.7 / 3.8	0.117 / 0.12	0.804 / 0.006	0.55 / 0.003	0.25	1	2.42 / 0.95	0.029 / 0.03	0.201 / 0.002	0.138 / 0.001

4 Conclusions and Future Scope

This study demonstrates that on-road air pollution exposure significantly affects inhaled dose among urban commuters in Tier 2 and Tier 3 Indian cities. The results reveal marked variation by transport mode, time of day, and road type. Pedestrians consistently experienced the highest inhaled doses—particularly during peak hours—due to close proximity to traffic emissions and elevated breathing rates. Among motorized modes, auto-rickshaw users were exposed to higher concentrations of pollutants, especially in the evening. Additionally, pedestrians traveling along arterial roads encountered substantially greater carbon monoxide (CO) exposure compared to those on collector roads, highlighting the influence of street typology on pollutant accumulation. These findings have broader implications for cities across South and Southeast Asia, where similar challenges in urban mobility, traffic congestion, and pollution exposure persist. For instance, (Saksena et al., 2008)) reported $PM_{2.5}$ exposure levels exceeding 100 µg/m^3 among commuters in Hanoi, especially during morning hours, aligning with the elevated doses observed in this study. Similarly, a study in Bogotá found high concentrations of $PM_{2.5}$ and black carbon across transport microenvironments, with personal exposure levels strongly associated with respiratory risk, especially among vulnerable commuters (Malagón-Rojas et al., 2022). These results echo our own, reinforcing the global pattern of disproportionate exposure among active and low-income travelers in rapidly urbanizing environments. Furthermore, the higher CO concentrations observed along arterial stretches in our study are consistent with patterns reported in urban street canyon studies in the UK, where CO levels vary by traffic volume and street design (Kaur et al., 2007). By integrating real-time air quality monitoring, land-use classification, and mode-specific inhaled dose estimation, this study offers a replicable framework for exposure analysis in low- and middle-income countries (LMICs). The approach can inform data-driven transport planning, including the development of low-exposure routes, infrastructure investments for vulnerable users, and timing strategies that reduce peak-hour exposure Meena et al. (2025). As (Mueller et al., 2015) emphasize, integrating health metrics into transport systems can produce dual benefits—reducing environmental burden and improving population-level health outcomes. However, this study is subject to certain limitations that should be acknowledged. All commuting trips were performed by a single trained user to maintain consistency in travel behavior and data collection. While this approach ensured methodological uniformity, it may not reflect variations in inhaled dose that could arise from differences in age, gender, walking pace, or individual travel patterns. The study also did not account for vehicle subtype differences, such as open versus enclosed auto-rickshaws or scooters versus motorcycles, which can influence exposure due to varying speeds, emission proximity, and levels of ventilation. Moreover, the monitoring was conducted over a single season, without capturing seasonal or meteorological variability that can affect pollutant dispersion and concentration levels.

Future studies should examine how inhaled dose fluctuates across multiple user profiles, vehicle subtypes, and seasonal conditions, providing a more representative understanding of exposure risks. Investigating the effects of operational driving behaviors—such as idling, acceleration, and congestion-related stop-and-go movements—would offer deeper insight into real-world emission dynamics. Furthermore, integrating personal health characteristics into inhaled dose estimation could enable targeted risk assessments, particularly for vulnerable populations. Expanding in these directions will enhance the applicability of exposure research and support the development of health-conscious, equitable, and environmentally resilient transport systems across both Indian cities and similar urban environments globally.

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