COMPARISON OF ULTRAFINE PARTICLES EXPOSURE IN DIFFERENT TRANSPORTATION MODES IN DHAKA CITY

By

SHAIKH ASHIK–UN-NOOR

A Thesis Submitted to the Department of Civil Engineering in
Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING (ENVIRONMENTAL)

DEPARTMENT OF CIVIL ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

Dhaka, Bangladesh

21 August 2021

The thesis titled "Comparison of Ultrafine Particles Exposure in Different Transportation Modes in Dhaka City." by Shaikh Ashik-Un-Noor, Roll No. 1018042106, Session: October 2018, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Environmental) on 21 August 2021.

BOARD OF EXAMINERS

Dr. Provat Kumar Saha Assistant Professor Department of Civil Engineering, BUET	Chairman (Supervisor)
Dr. Md. Delwar Hossain Professor and Head Department of Civil Engineering, BUET	Member (Ex-Officio)
Dr. Muhammad Ashraf Ali Professor Department of Civil Engineering, BUET	Member
Dr. Sheikh Mokhlesur Rahman Assistant Professor Department of Civil Engineering, BUET	Member
Dr. Abdus Salam Professor Department of Chemistry, University of Dhaka	Member (External)

ii

DEDICATED TO

MY PARENTS

&

MY FRIENDS

Declaration

It is hereby declared that except for the contents where specific references have been made to the work of others, the studies contained in this thesis are the results of investigations carried out by the author under the supervision of Dr. Provat Kumar Saha, Assistant Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka. No part of this thesis has been submitted to any other universities or educational establishments for a Degree, Diploma, or other certifications (except for publication).

Shaikh Ashik-Un-Noor

iv

Abbreviation

UFP - Ultra Fine Particles

PM - Particulate matter

PNC -Particle Number Concentration

GIS - Geographic Information System

GPS - Global Positioning System

CPC - Condensation Particle Counter

RAMP - Real Time, Affordable, Multi-Pollutant

Abstract

Ultrafine particles (UFP) are airborne particles with a size of less than 100 nm. Due to their smaller size and presence in the air in large numbers, they pose a serious health risk. This study measures and compares in-vehicle UFP concentrations in selected transportation modes in Dhaka city, Bangladesh. Transportation modes are: (i) public bus, (ii) private car with windows open, (iii) private car with windows closed and air recirculation off, (iv) private car with windows closed and air recirculation on, and (v) Rickshaw. UFP concentrations are measured as total particle number concentrations (PNC), a commonly used metric for UFP. About 10 days of repeated measurements were collected in each transportation mode on a selected route in different parts of the day (morning, mid-day, afternoon). Results indicate that (1) in-vehicle PNCs vary by transportation mode, higher in the public bus and private car with open windows and lower in the private car with closed windows and air recirculation on. The inter-modal variations are about a factor of two. (2) In all selected transportation modes, the in-vehicle PNCs are substantially higher than the urban background level; they are about 4-8 times higher in the public bus and private car with open windows and 2-4 times higher in the private car with closed windows and air recirculation on. (3) In-vehicle PNCs vary spatially and temporally. For all selected transportation modes, concentrations are typically higher in the morning than in mid-day and afternoon. Spatial variations (a factor of 2-4) are much larger than temporal variations (a factor of 1.2-1.8). (4) Substantially higher in-vehicle PNCs and their inter-modal variations have implications on PNC personal exposures. About 1-2 hours commuting time (4-8% of daily hours) contributes 20-35% of daily PNC exposures. These exposures are higher for public bus commuters and lower for private car commuters, specifically, those who commute with car windows closed and air recirculation on. (5) Inter-modal variations of in-vehicle PNCs are linked with exposure disparity among commuters' income groups. The commuters in the lower-income group (< BDT 25K per month) have about 20% higher exposure than the higher income group (> BDT 75K per month). Results from this study could help to design appropriate mitigation measures for reducing personal exposure to UFP.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

Acknowledgement

First, all praises are for the almighty who provided me with the opportunity to complete this research. This research was completed with the encouragement and valuable help from some important personalities.

I wish to express my heartfelt and sincere gratitude to, Dr. Provat Kumar Saha, Assistant Professor, Department of Civil Engineering, BUET, for his supervision, encouragement, guidance in all stages of this work. I am in debt to him for the constructive criticism and the valuable time he had given during the research work.

I would also like to thank my friend Prottoy for helping with the field data collection of my research.

I acknowledge the support of officials and staffs of the Department of Civil Engineering, BUET in different phases of my research work.

Last but not the least; I express my profound gratitude to my parents and friends for their patience and active support.

CHAPTER 1
INTRODUCTION

1.1 Background of the Research

Airborne ultrafine particles (UFP; commonly defined as particles with a diameter smaller than 100 nm) have significant and poorly understood health effects..[1] $PM_{2.5}$ (particles with a diameter smaller than 2.5 m) mass concentrations are now regulated by health-based standards. UFP provides very little mass to the overall $PM_{2.5}$ mass because to their small size, but they are the major contributor to particle number concentrations.[2] As a result, the total particle number concentration (PNC, typically express in a unit of # particles/cm^3) is the most commonly used metric for quantifying ambient UFP concentration.[3] There is widespread concern that the adverse health effects of UFP exposure may be different from those of bigger particles. Multiple toxicological research[4–8] have found that UFP can penetrate deeper into the lungs, can translocate to the brain, and is potentially more harmful than larger particles. However, due to limitations in the characterization of UFP exposures, there are significant ambiguities in the evidence of health impacts of airborne UFP.

Local sources and various complex physiochemical processes such as dilution, coagulation, evaporation, and condensation heavily influence exposure to UFP concentrations in metropolitan environments[9–11], and largely vary spatially and temporally[12,13] within an urban area. Therefore, UFP exposure characterization needs high spatial and temporal resolution data in comparison to $PM_{2.5}$ mass concentrations[14,15]. However, UFP monitoring data are rare because of the high monitoring cost and complexity[16]. While limited $PM_{2.5}$ monitoring data exist in Dhaka city[17], there is no data on UFP exposures.

Traffic emissions are a significant contributor to UFP concentrations in urban areas[1,12,18] Daily commutes contribute disproportionately to overall daily exposure to UFP.[19] According to a research conducted in Los Angeles[20], time spent driving in automobiles accounts for 33%–45% of overall UFP exposure.. The commute time in Dhaka city of Bangladesh is substantially higher than many mega cities in the world due to severe traffic congestion.[21] Therefore, the exposure to UFP during daily commuting likely substantially higher in Dhaka city compared to many other megacities. However, no in-vehicle UFP characterization data exist for Dhaka city. The UFP exposure levels may vary with the choice of transportation mode, meteorology, vehicle fleet composition, and route. The choice of transport mode depends on the socio-economic status of the commuters.[22] Thus, personal exposure to UFP and other urban air pollutants, and socio-economic inequality are likely linked. The focus of this study is to characterize the in-vehicle UFP exposures from commuting in the context of Bangladesh, specifically Dhaka City.

1.2 Study Objectives

This study aims to characterize the UFP exposures in selected transportation modes in Dhaka city. The selected transportation modes are public bus, private car, and rickshaw. The specific objectives are:

1. Measure UFP concentrations in public bus, private car, and rickshaw.
2. Determine factors influence the inter-modal variation of exposure concentrations, and
3. Assess the implications of in-vehicle UFP exposures on personal exposures and socio-economic status of commuters.

1.3 Scope of Research

The primary focus of this research is to characterize the UFP concentrations in common transportation modes in Dhaka city. The main scopes of this research are outlined below:

1. Providing quantitative estimates of UFP exposures for selected transportation modes in Dhaka city (i.e., public pus, private car, and rickshaw).
2. Providing guidelines to propose and design mitigation measures for reducing personal exposure to UFP.

1.4 Organization of the Thesis

This thesis is presented into 5 chapters. The first chapter describes the background and objectives of the study. Chapter 2 describes the relevant past studies and technical features. Chapter 3 describes the study methodology and data collection. Chapter 4 describes the results and discussion. The final chapter, chapter 5, describes the conclusions and recommendations.

CHAPTER 2
LITERATURE REVIEW

2.1 General

Owing to the potential adverse effects on health, in-vehicle exposures to UFP have gained worldwide attention in recent years. Epidemiological and toxicological studies have demonstrated that the health impacts of UFP is potentially greater than larger particles. They can induce health effects due to their unique physical and chemical properties. In this chapter, recent literature has been reviewed to summarize the sources, physio-chemical nature, in-vehicle exposures, and health effects of UFP. The goal is to identify motivations and knowledge gaps in in-vehicle UPF exposure study in the context of Bangladesh.

2.2 Ultrafine Particles (UFP)

The ultrafine particle is a subset of fine particulate matter ($PM_{2.5}$). $PM_{2.5}$ refers to aerodynamic particles with a diameter of 2.5 microns or less. UFP refers to aerodynamic particles with a diameter of 0.1 microns (100 nm) or less.

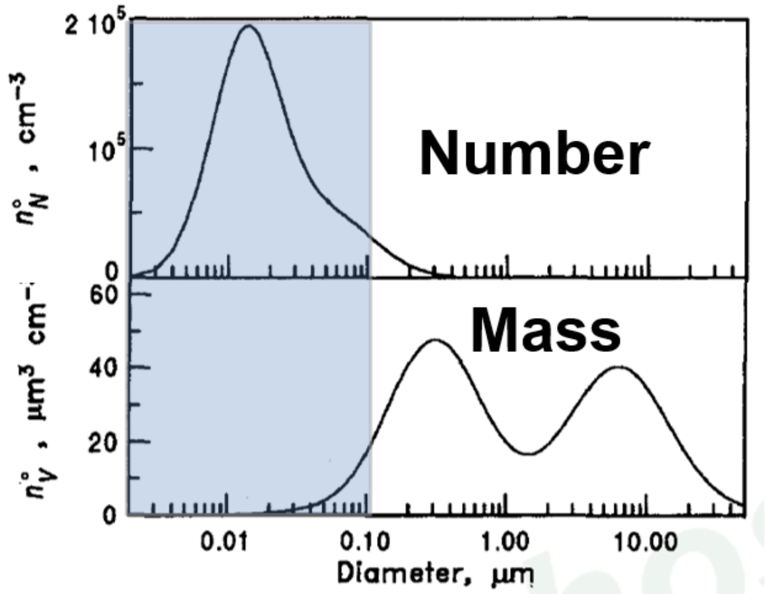

Figure 2.1: Typical number and volume size distribution of atmospheric particles (source: Seinfeld and Pandis (2006)[23])

In practice, UFP is characterized by total particle number concentrations. This is because they have tiny mass but substantially higher number concentrations.[3] Figure 2.1 shows the typical number and volume-weighted size distributions of ambient particles. The number size distribution of more than 90% of ambient particles falls below the 100 nm range. (See Figure 2.1). This provides the rationale for using total number concentrations as a metric for characterizing UFP. On the other hand, as expected, the mass (~ volume) concentrations of particles below 100 nm are tiny, typically less than 5% of total mass concentrations of respirable airborne particles.

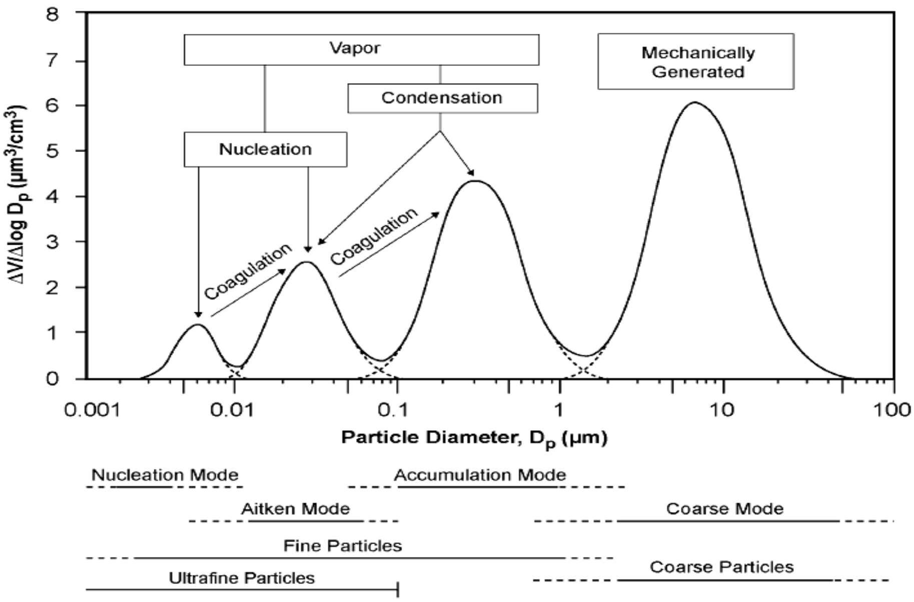

Figure 2.2: Various size-based modes of atmospheric particles (source: Araujo and Nel[24])

Figure 2.2 shows the various size-based of atmospheric particles. In terms of modes, particles are classified as nucleation mode, Aiken mode, accumulation mode, and coarse mode. The UFP falls under nucleation and Aitken mode particles. These particles are either form from gas-to-particle conversion (nucleating particles) and coagulation of these nucleating particles. However, other than coagulation, the Aitken mode particles can be directly emitted from combustion sources, such as traffic[25] $PM_{2.5}$ are mostly dominated by accumulation mode,. PM_{10}refers to aerodynamic particles with a diameter of 10 microns or less. PM_{10} is dominated by coarse mode (See Figure 2.2).

2.3 Key Differences between UFP, $PM_{2.5}$ and PM_{10}

Because of the smaller size, on a per unit mass basis, UFP has substantially higher surface area compared to $PM_{2.5}$ and PM_{10}. Figure 2.3 shows a comparison between particles with three specific sizes (10 µm, 2.5 µm, and 0.1 µm). For a per unit mass, the number concentrations of a 0.1 µm particle is 1,000,000 times greater compared to a particle of 10 µm; the total surface area is about 100 times greater.

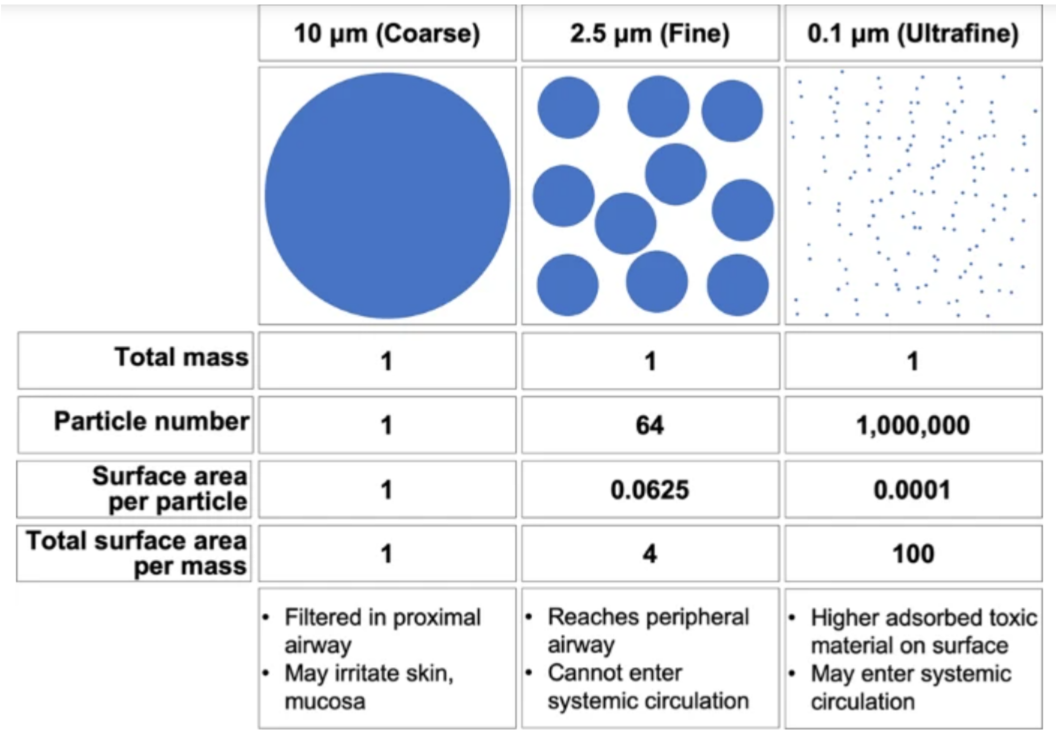

Figure 2.3: Comparison of PM_{10}, $PM_{2.5}$, and $PM_{0.1}$ (source: Kwon et al.[26])

Due to the higher surface area, ultrafine particles can likely absorb toxic materials (e.g., various carcinogenic organics, metals). They may enter the systemic circulation system (bloodstream) of the human body.[4,27] On the other hand, $PM_{2.5}$ may reach the peripheral airway but cannot enter the systemic circulation system. PM_{10} usually filters out in the proximal airway. Furthermore, due to the unique physio-chemical nature, UFP shows substantially higher spatial-temporal variability than the larger particles.[1,3]

2.4 Major Sources of Ambient Ultrafine Particles

There are several origins of atmospheric UFP, including natural and anthropogenic sources. Among the anthropogenic sources, combustion process is the primary one. Most of particles emitted by engines are in the ultrafine particle size range. In general, traffic and nucleation are the major source of UFP. For example, a source apportionment study of ambient particle number concentration in Los Angeles apportions about 67% to traffic and 17% to nucleation.[28] Posner and Pandis[29] reported that gasoline automobiles are responsible for 40% of ultrafine particle number emissions in the eastern United States. Industrial sources came in second with 33%, followed by non-road fuel (16%), on-road fuel (10%), as well as coal combustion and dust (1%). Many other studies[1,15,18,30] identified the traffic and nucleation are the major sources of UFP.

Apart from the traffic, commercial cooking emissions from restaurants is an important source of UFP in many urban locations.[15] Natural gas combustion for cooking and household activities, wood combustion for cooking and heating are the residential sources of UFP.[31] Air traffic could be an important local source for UFP in area near big airports.[32] Nucleation particles form in the atmosphere through atmospheric chemistry.[33] However, nucleation is typically a regional phenomenon. Nucleation particles are relatively uniformly distributed across an urban area.

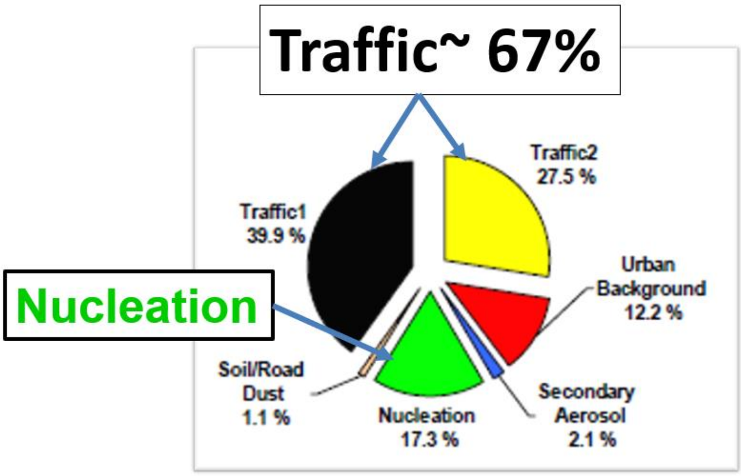

Figure 2.4: Source apportionment of ambient particle number concentrations in Los Angeles (source: Sowlat et al.[28])

Ambient UFP is abundant in the urban areas with road traffic as their principal source[12]. Studies have frequently reported significant high concentrations of UFPs near major freeways.[1] Many studies investigated UFP concentrations along highways and observed elevated concentrations within the first 100 m of the roadway[11,14,34]. For example, measurements of near-road particle number size distribution at various downwind distances from the Interstate 710 freeway in Los Angeles highway (See Figure 2.5) have shown substantial elevated concentrations within first 20 m. Concentrations rapidly decay as one moves away from the road.[9] Ambient UFP concentrations vary substantially with season, and time of the day.[16]

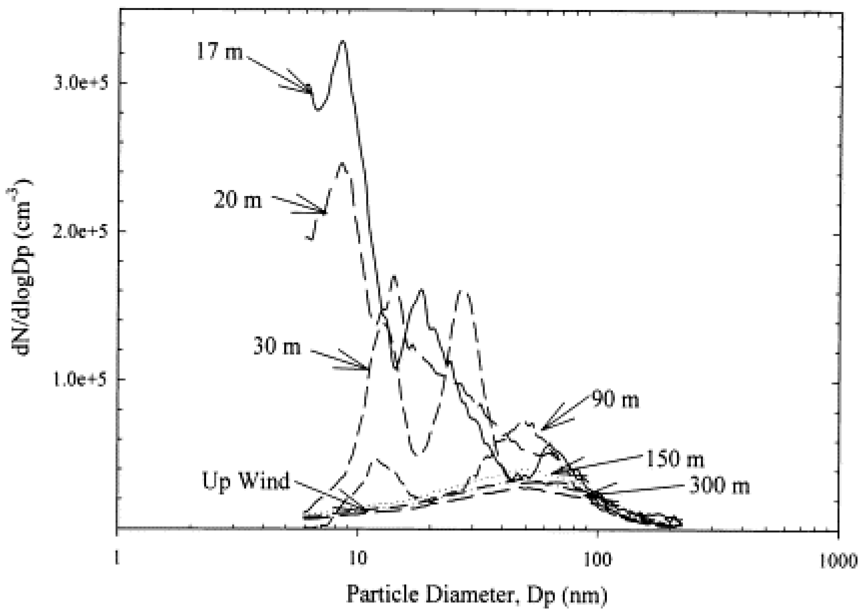

Figure 2.5: Particle number size distributions measured at various distances from the Interstate 710 freeway in Los Angeles highway(source:Zhu et al.[34])

2.5 In-vehicle Exposures of Ultrafine Particles

Since traffic is one of the major sources of UFP[12], numerous studies have reported significant contribution of UFP from commuting to daily exposure [19,35]. Since on-road/near-road UFP concentrations are, in general, substantially higher than urban background concentrations (see Figure 2.5), these particles can easily penetrate to the in-vehicle system depending on the insulation system. In general, factors that increase air exchange rates (AER) inside the vehicle increase UFP indoor/outdoor (I/O) ratio. Hudda et al. [36] reported that ventilation, vehicle age or mileage, and driving speed explain about 80% of the variability in measured UFP I/O ratios in a study in Los

Angeles and Sydney. Figure 2.6 shows the measured relationship between I/O Ratio of UFP and Air Exchange Rate (AER) in this study. As expected, compared to the re-circulation, the UFP I/O is substantially higher under outside air intake condition.

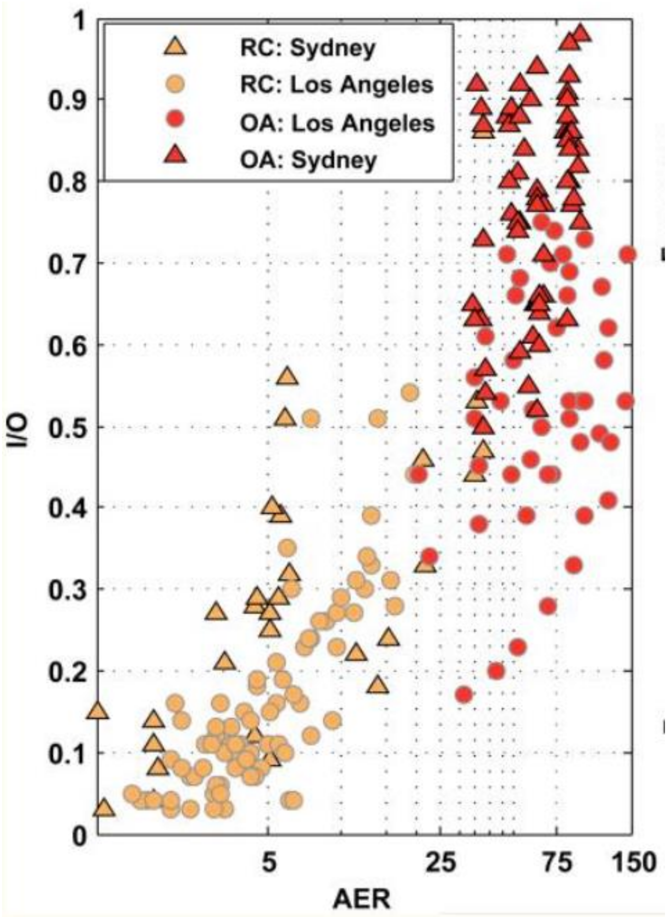

Figure 2.6: The measured relationship between Indoor/Outdoor Ratio of UFP and Air Exchange Rate (AER) in a study in Sydney and Los Angeles. (Source: Hudda et al.[36]) (RC: recirculation -in-cabin air is re-circulated; OA: outside air intake- outside air is drawn into the vehicle cabin)

The influence of in-vehicle UFP concentration on personal exposures are reported in a series of past studies. A micro-environmental study in Los Angeles reported that 33%-45% of Los Angeles residents' overall UFP exposure was attributed to commuting time spent in cars[35]. Another study on Los Angeles Freeway, reported that 10 to 50 percent of daily exposure to traffic-induced UFP was from 1-hour commute[19]. The comparatively short duration during commuting can add significantly to everyday personal exposure and associated health effects. Commuting during peak hours can lead to substantial increase of UFP exposure, regardless of the mode of commuting.[37] Substantial inter-modal variations are reported in multiple transport microenvironments studies worldwide.[38–40]

Many factors affect the exposures to UFP during commuting, including traveling hours and days (e.g., peak versus off-peak hours, weekdays versus weekends), travel modes, and travel path features (e.g., road configuration, micro-meteorology, wind speed, traffic volume and composition)[38,41–43]. For examples, Goel and Kumar[44] reported that despite consuming only 2% of travel time at a signalized traffic intersection can contribute ~25% of the overall commuting exposure. Hertel et al.[45] reported that for low exposure routes, the total air pollution exposure caused by traffic was 54-67% lower relative to high exposure routes and 5-20% lower while driving outside the peak traffic hour. In a study in Hong Kong, Li et al.[46] reported that commuters were exposed to significantly higher $PM_{2.5}$ concentrations in winter than in summer.

Studies also investigated the effect of car microenvironments in comparison to other forms of transports, where recirculation environment resulted in a decrease of in-car $PM_{2.5}$ concentration. For car-driving with windows-open, $PM_{2.5}$ levels are usually the highest[47]. In a field study in Sacramento, California, a reduction of up to 75% was recorded relative to windows-open environments[48]. Another study in Istanbul (Turkey) reported the lowest $PM_{2.5}$ concentrations with air recirculation ON.[43]

2.6 In-vehicle UFP Personal Exposures and Socio-Economic In-equality

The influence of air pollution exposures is not evenly distributed. The effects vary by location, race, ethnicity, income, and many other socio-economic factors.[49] In the US, the racial-ethnic minority populations are subjected to higher air pollution exposures.[50] Higher exposures for low-come people are also reported in many studies.[49] Exposure disparities for in-vehicle personal exposures have been reported in several studies.[51,52]In general, higher exposure concentrations for the most disadvantaged socio-economic group are reported in the majority of these studies. Children in lower social-class families in Leicester appear to live in areas with high levels of pollution than wealthier families living in low-emission zones.[53]

2.7 Adverse Health Effects of Ultrafine Particles

Ultrafine particles are smaller than cellular structures and can cross directly into the blood stream[1,54,55]. Ultrafine particles have a high deposition fraction, which means that the wide surface area of ultrafine particles increase the ability to penetrate the lungs and move to other areas of the body[1,56].The harmful effects depend on their size, shape, chemical composition, density of particles, how far in the respiratory tree these particles can go, how long they take to settle in and what they do as they deposit.[27,57] The chemical and toxic properties of the particles (its composition) determine what occurs as it is stored in the respiratory system.

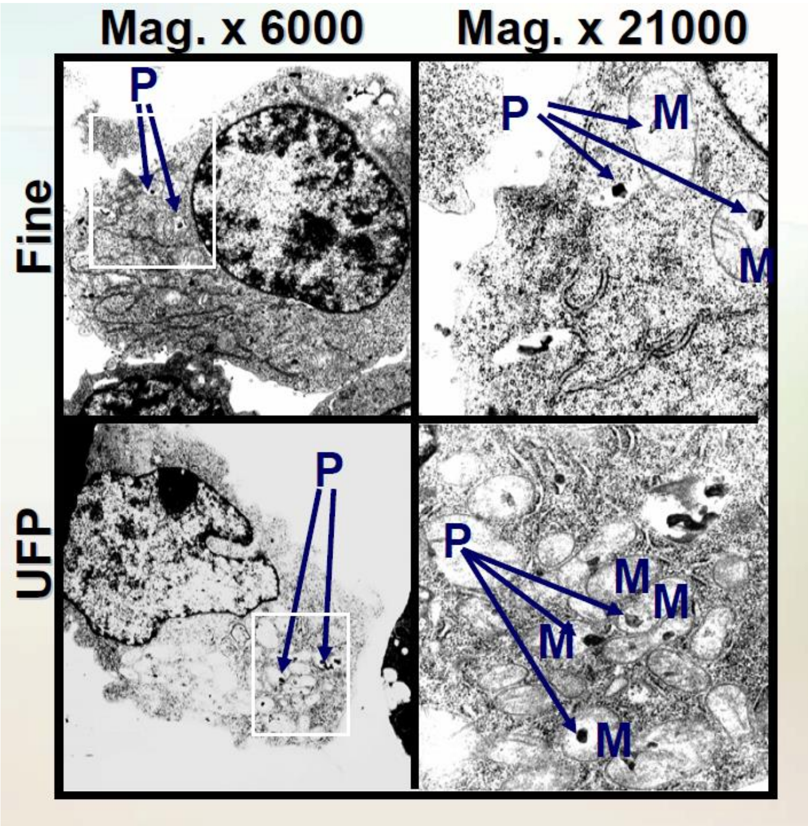

Figure 2.7: Comparison of oxidative stress and mitochondrial damage due to exposure of $PM_{2.5}$ and UFP (Source: Li et al.[5])

Many toxicological studies have reported greater health effects for UFP than $PM_{2.5}$. For example, Li et.al. [5]compares the oxidative stress and mitochondrial damage due to exposure of $PM_{2.5}$ and UFP (Figure 2.7). Higher mitochondrial damage was observed due to UFP.

While numerous toxicological studies[1] suggest that the health effects of ultrafine particles are greater than larger particles, the long-term epidemiological effects of ultrafine particles independent to $PM_{2.5}$ are largely uncertain.[1,58] This is mainly due to the lack of exposure assessment data for the ultrafine particles. Up to date, a large portion of epidemiological studies on airborne particles have focused on combustion particles from gasoline- and diesel- powered motor vehicles. Since traffic is the main source of UFP, most combustion particles are UFP. The particles from such sources have the clearest close association with significant health effects such as DNA damage. Like, $PM_{2.5}$, ultrafine particles cause numerous health damage, including cardiovascular effects, pulmonary effects, blood effects, prenatal outcomes and neurotoxic effects.[1] Figure 2.8 summarize these effects.

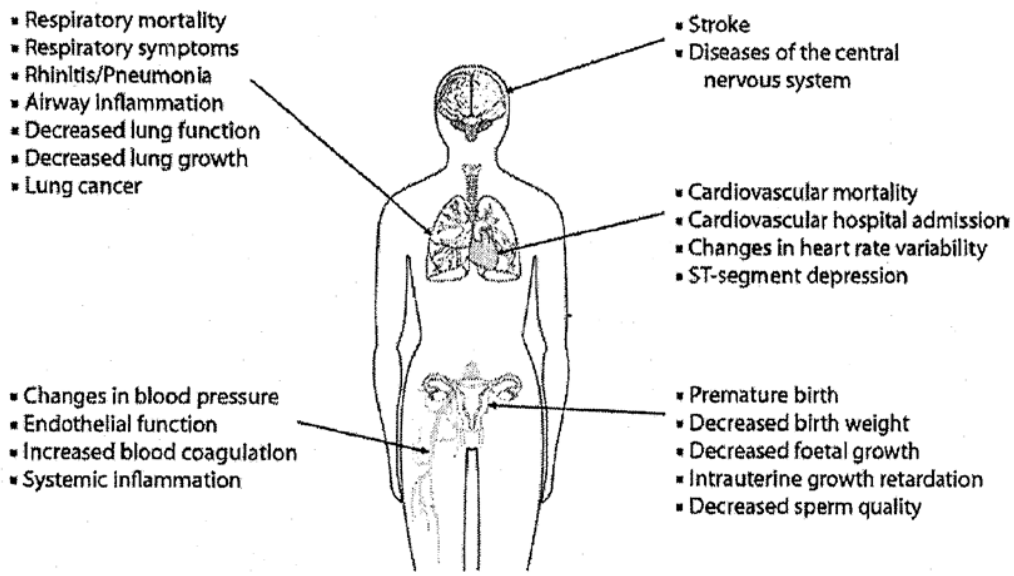

Figure 2.8: Organs of human body that can be affected by UFP. (Source: Peters, et. al.[59])

2.8 Particulate Air Pollution Exposures in Dhaka City of Bangladesh

While the Dhaka City of Bangladesh frequently experiences very high particulate pollution episodes, the existing research on particulate matter exposure is limited. The ambient $PM_{2.5}$ levels are in general 5-10 times higher than the National Ambient Air Quality Standards. Particulate pollution in Bangladesh follows a strong seasonal pattern. Concentrations are about 2-4 times higher in the winter compared to the rainy seasons.[17,60–62]

Local and regional sources govern the particulate pollution levels in Dhaka city.[62] A $PM_{2.5}$ source apportionment study[61] reported that traffic, biomass burning in the brick kilns, construction dust are the major sources for $PM_{2.5}$. The concentrations are higher during the winter due to seasonal sources (brick kiln) and meteorology. The presence of various toxic heavy metals in the respirable particles is reported.[63] In addition to the local source, a study reported the large influence of transboundary air pollution on the $PM_{2.5}$ levels in Dhaka city.[64]

Although there is limited information on $PM_{2.5}$ concentrations in Dhaka city, there is no existing study on ultrafine particles. The in-vehicle exposure study is also limited. A recent study[47] measured in-car $PM_{2.5}$ concentrations across Dhaka City under various ventilation conditions. Substantial reduction of $PM_{2.5}$ concentrations under air-recirculation on is reported, similar to many other past studies.

2.9 Knowledge Gaps on In-vehicle UFP Exposures

The literature review identified the following gaps in knowledge on in-vehicle ultrafine particles exposures:

a. Various studies have reported substantial variations in intra- and inter-modal in-vehicle UFP exposures. A recent study[47] has reported in-car $PM_{2.5}$ measurements in Dhaka city, Bangladesh. However, intra-, and inter-modal in-vehicle UFP exposures variations in polluted megacity remain mostly unexplored.
b. Although numerous past studies have reported the substantial spatial and temporal variability of UFP, how this dynamic nature of UFP influence in-vehicle UFP exposures for commuters in a polluted megacity remain unexplored.

c. Many studies have found a strong link between air pollution exposures and demographic covariates such as race, ethnicity, and income. These studies have mainly been conducted in Europe and America. No study has explored the link between air pollution exposures and demographic covariates in the context of Bangladesh.

2.10 Summary

This chapter summarizes the recent literature on UFP sources, health effects, in-vehicle exposures. A large body of literature reported the importance of traffic as a major source of UFP and effects in-vehicle UFP exposures. The health effects of UFP are generally greater than larger particles, but evidence remains inconclusive. The ambient concentrations and in-vehicle exposures of UFP in polluted megacity remain unexplored.

CHAPTER 3
METHODOLOGY

3.1 General

This chapter describes the measurements conducted to characterize in-vehicle UFP exposures in selected transportation modes in Dhaka City. This study collected repeated measurements of UFP concentrations and various other spatio-temporal variables in a selected route in Dhaka City for selected transportation modes: public bus, private car, and rickshaw. These measurements, along with transportation modal choice survey data, were analyzed to characterize the implications of measured in-vehicle UFP concentrations on personal exposures.

3.2 Study Area and Measurements Routes

Measurements were carried out on the selected routes in Dhaka City. Dhaka city of Bangladesh is one of the densely populated cities in the world. There is about 8.9 million people live within the city boundary and 21 million people live in the Greater Dhaka. According to Bangladesh Road Transport Authority (BRTA) data, there are 8459 minibuses on 149 routes and 166,840 private cars (source: www.brta.gov.bd) in the Dhaka city.

Measurements were carried out in March 2020 and October 2020. The measurements routes are shown in Figure 3.1. Most of the measurements were conducted on a selected route (i.e., Azimpur to Mirpur; 8.9 km; green line in Figure 3.1, hereafter refer as “primary route”). This is one of the main arterial roads in the Dhaka City. This route is selected because measurements for all the selected transportation modes (public bus, private car, and rickshaw) are possible to conduct in this route. A subset of measurements was conducted on a bigger route (33 km) that covers all major roads in the Dhaka city (green line + red line in Figure 3.1).

3.3 Measurements of In-vehicle UFP Concentrations

Measurements were performed in three selected transportation modes: public bus, rickshaw, and private car. For in-car sampling, measurements were collected under three different ventilation conditions: a) window open, b) window closed with air conditioning on, but air recirculation off, and c) window closed with air conditioning on, and air recirculation on.

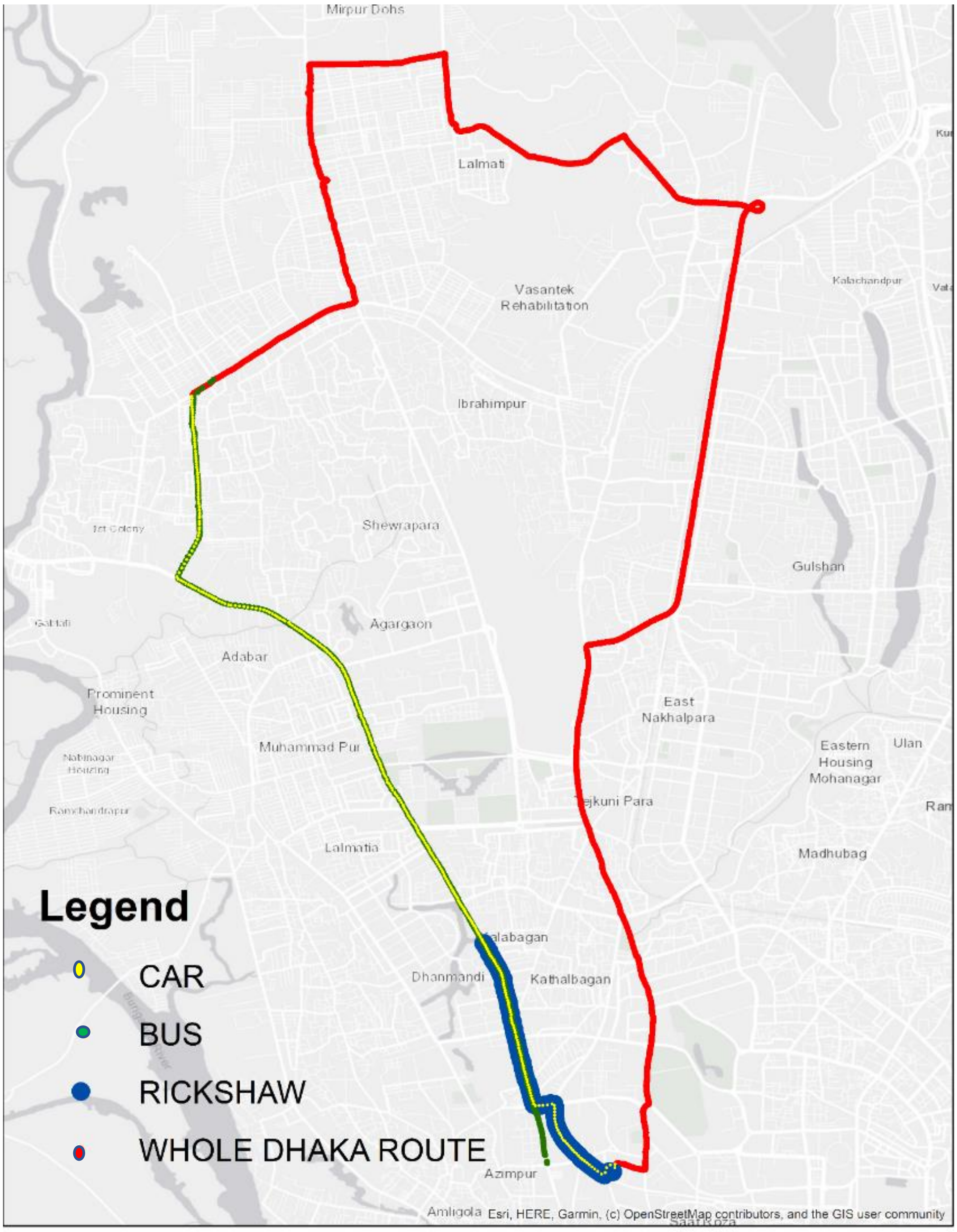

Figure 3.1: Selected routes for in-vehicle measurements of UFP concentrations.

For each transportation mode (total five modes: bus, rickshaw, and car under 3 ventilation configurations), measurements were conducted for ~10 days. To capture the variability in meteorology and traffic conditions, 10 measurements for each mode were distributed across the different part of the day (morning: 8-10 am, mid-day: 11 am - 2 pm, and afternoon: 3 pm -6 pm). For sampling on primary route, each trip was a round trip (Azimpur to Mirpur-1 and Mirpur-1 to Azimpur). It is noted that, the rickshaw sampling was collected at a sub-section of primary route (dark green line in Figure 3.1). This is because rickshaw is not allowed to run on all part of the selected route. Only a subset of car samplings (i.e., 3 trips for each ventilation condition) was carried out on the additional route (green line + red line in Figure 3.1).

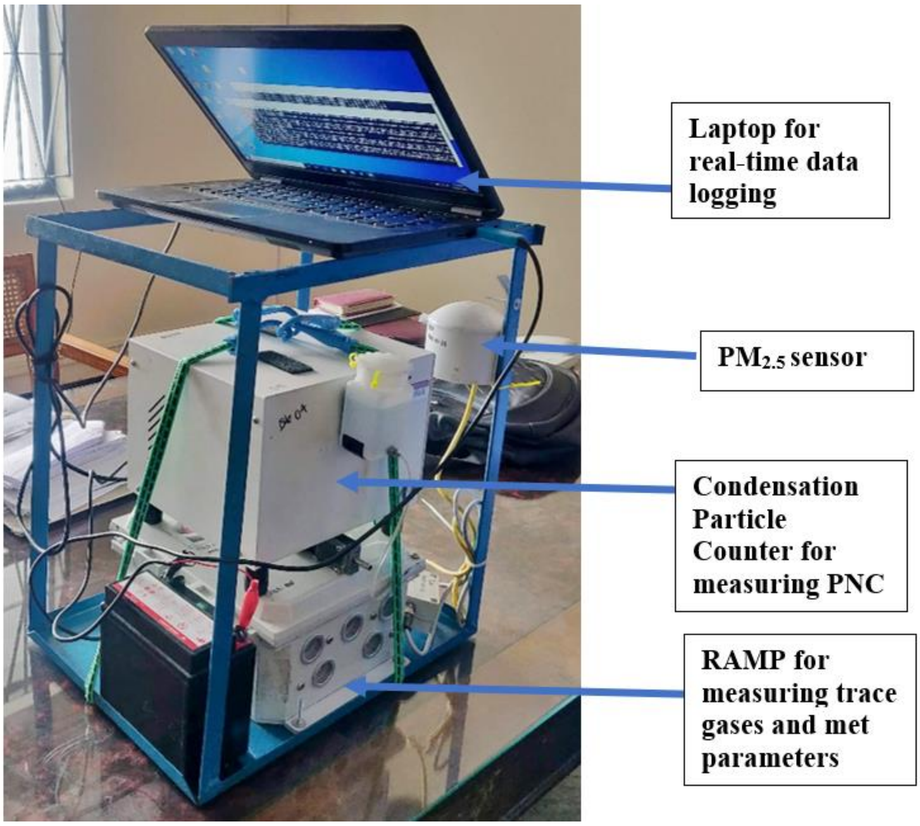

Figure 3.2: A photo of the instrumental setup used for measurements of UFP and other air pollutants concentrations.

Figure 3.3: A photo with instrumental setup inside a car during in-car data collection.

3.4 Instrumentation and Data Analysis

Total particle number concentrations (PNC) were measured using a water-based Condensation Particle Counter (CPC; Aerosol Devices Inc.; MAGIC 200P model[65]; lower size cut 5 nm, sample flow rate: 0.3 L / min) as a measure of UFP concentrations. The lower detection limit of a CPC is 1 particle / cm^3 and upper limit is up to 10^5 particles / cm^3. In addition to the UFP data, the measurements of $PM_{2.5}$ (Purple Air, Plan-tower PMS 5003 laser sensor), several trace gases (CO, NO, NO_2, O_3), and basic meteorological parameter (temperature, relative humidity) were collected using the Real-time, Affordable, Multi-Pollutant (RAMP) monitor[66]. The concurrent GPS measurements were recoded to get the spatial location of the data.

All data were logged in real-time using a laptop. The logging frequency of PNC and GPS data was 1 s. Data logging frequency for other supporting data frequency was 1 min. Figure 3.2 shows a photo of the instrumental setup used for collecting UFP and other supporting measurements. Cellphone apps was used for recording GPS data.

The collected raw data were first reviewed for data quality assurance. For example, any suspected measurements (e.g., PNC measurements > 10^5 particles) were removed. The data from different instruments were aligned based on GPS time stamp. Quality-assured data were averaged temporally (e.g., trip average concentrations for a particular day) and spatially (e.g., average over 100 m road segments). These time and spatially averaged concentrations were used to explore the differences in exposures across transportation modes, pollutants, sampling locations, and time-of-a-day.

3.4 Transportation Modal Share and Socio-economic Status Survey

A questionaries survey was conducted to gather information on distribution of modal share by socio-economic status of the commuter in Dhaka city. *Appendix-A* shows the questionnaire used for this survey. A questionnaire was formed with choice of transportation mode, typical daily commute time, and various demographic and social factors including gender, age, income level, education, ownership of car. The survey was primarily conducted among the selected population along the primary route. But samples from other part of the Dhaka city were also taken. A total of 374 people were participated in this survey. To determine whether this survey sample is representative, a simple calculation of optimal sample size (n) was determined using the method of Kothari et al.[67] For a given size of the population (N), this methods provide the optimum sample size.

$$n = \frac{z^2.p.q.N}{e^2(N-1)+z^2.p.q} \tag{3.1}$$

Where,

n = size of sample

N = size of population

z = the z-value of desired degree of confidence

p = the population proportion of households of interest

e = the absolute size of error

q=1-p

3.5 Summary of Methodology

To characterize the in-vehicle UFP exposures in the public bus, private car, and rickshaw, about ten days of repeated measurements of particle number concentrations were collected in selected modes. Figure 3.4 provides a summary of data collection and analysis methodology. Measurements were conducted on the selected routes, covering diverse meteorological conditions. These high-time resolution monitoring data were analyzed to compare the intra and inter-vehicle variability of measured concentration, factors that affect the variability, and their implications on personal exposures.

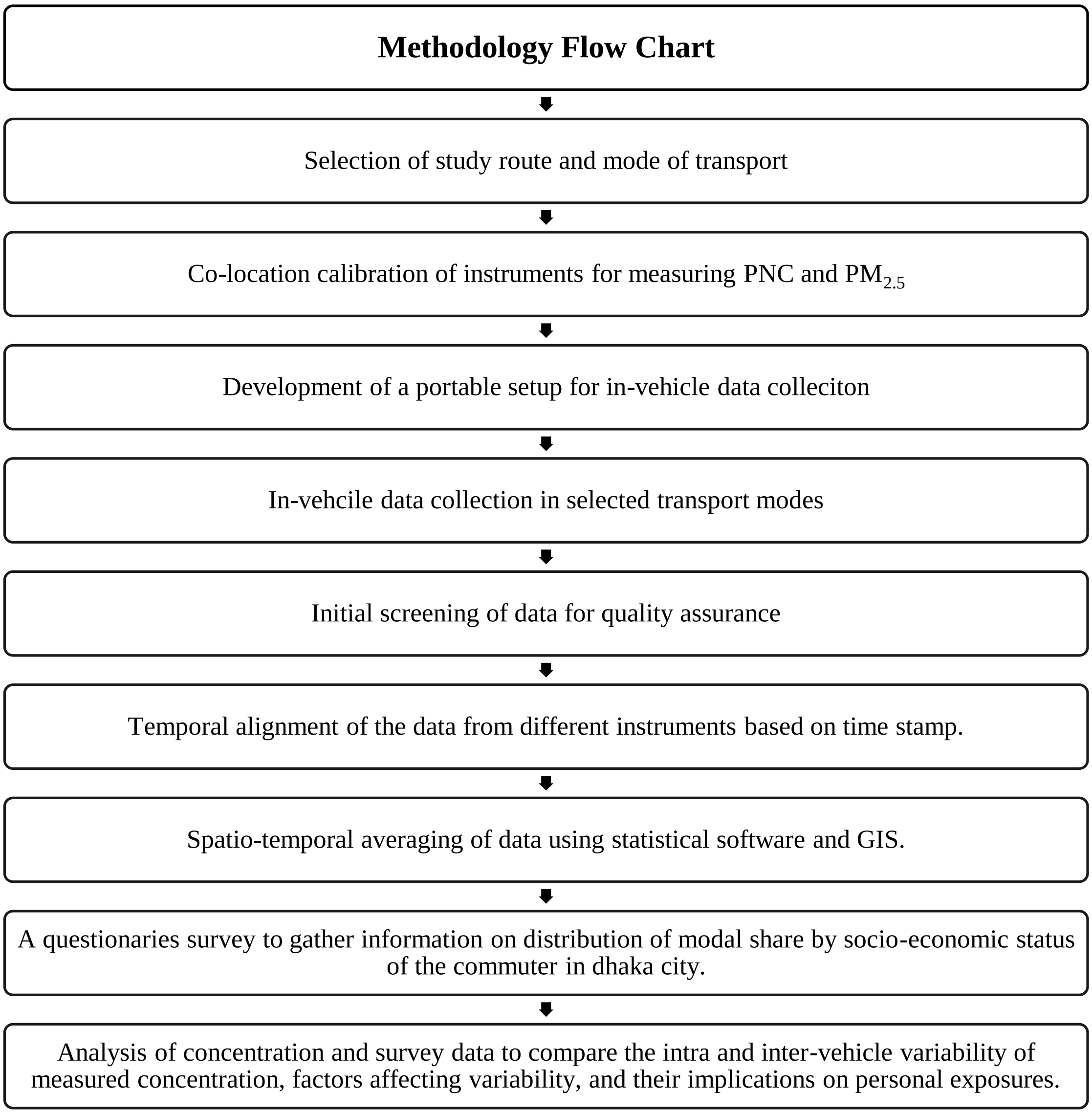

Figure 3.4: A summary of data collection and analysis methodology

CHAPTER 4
Results and Discussions

4.1 General

This chapter reports the summary of in-vehicle UFP concentrations in three transportation modes: public bus, private car, and rickshaw. Measurements are used to quantify the intra- and inter-modal variability of UFP exposures and factors that influence that variability. Finally, the measured concentrations data are used to explore the contribution of in-vehicle UFP exposures to daily personal exposures for a typical commuter in Dhaka city by transportation mode. Analyses are also shown for how the in-vehicle exposures could vary with the socio-economic status of a commuter.

4.2 UFP Concentrations in Different Transportation Modes

Table 4.1 and Figure 4.1 compare the measured study average UFP concentrations (particle number concentrations: PNC) and co-measured $PM_{2.5}$ concentrations in different transportation modes. Comparison is also made with the average PNC measured at an urban background location in Dhaka city. Urban background PNC are continuous measurement of outdoor concentrations at a residential location in Dhaka city collected over two months (March and July 2020).

The measured in-vehicle PNC shows a substantially variably across transportation modes. Concentrations are higher in public bus and private car with windows open. The in-car PNC with window-open is almost similar to the concentration measured in public bus. However, in-car PNC under window-closed condition strongly depends on whether the air recirculation was on or off. Relative to the window open condition, the average PNC with window-closed condition was ~12% lower under air recirculation off condition, and 47% lower under air recirculation on condition.

Table 4.1: Average PNC and $PM_{2.5}$ concentrations in various transportation modes.

Measurement locations	Number of sampling days				Average trip time (minutes)	PNC (#/cm³) Mean ± SD	$PM_{2.5}$ (µg/m³) Mean ± SD
	Total	M[1]	N[2]	AN[3]			
Public Bus	9	4	3	2	80	80,000 ± 35,000	200±80
Private Car: Window Open	10	2	4	4	71	76,000 ± 29,000	160 ± 80
Private Car: Window Closed, Air Recirculation off	10	3	4	3	72	67,000 ± 35,000	140± 80
Private Car: Window Closed, Air Recirculation on	10	2	5	3	73	40,000± 20,000	70 ± 40
Rickshaw	9	-	2	7	44	54,000 ± 27,000	110 ± 60
Urban background	40				N/A	16,000 ± 5,000	N/A

M[1]= morning (8-10 am), N[2]= Noon (11 am - 2 pm), AN[3] = afternoon (3 pm - 6 pm)

Table 4.1 compares the average PNC and co-measured $PM_{2.5}$ concentrations in various transportation modes. PNC and $PM_{2.5}$ concentrations are strongly correlated. If a mode has measured higher PNC, the $PM_{2.5}$ is also higher in that mode and vice versa. For example, both PNC and $PM_{2.5}$ concentrations are the highest in the public bus, followed by the private car with the window open.

Relative to the window open condition, both PNC and $PM_{2.5}$ concentrations are substantially lower under window closed with air recirculation on. However, the relative reduction was higher for $PM_{2.5}$ (55%) than for PNC (47%). This is consistent with previous in-car sampling for $PM_{2.5}$.[47] A reduction up to 80% was reported for in-car $PM_{2.5}$ sampling with window closed with air recirculation on. *Appendix-B* provides further details on the comparison of PNC and $PM_{2.5}$ measured in various transportation modes at a different part of the day on primary and additional routes.

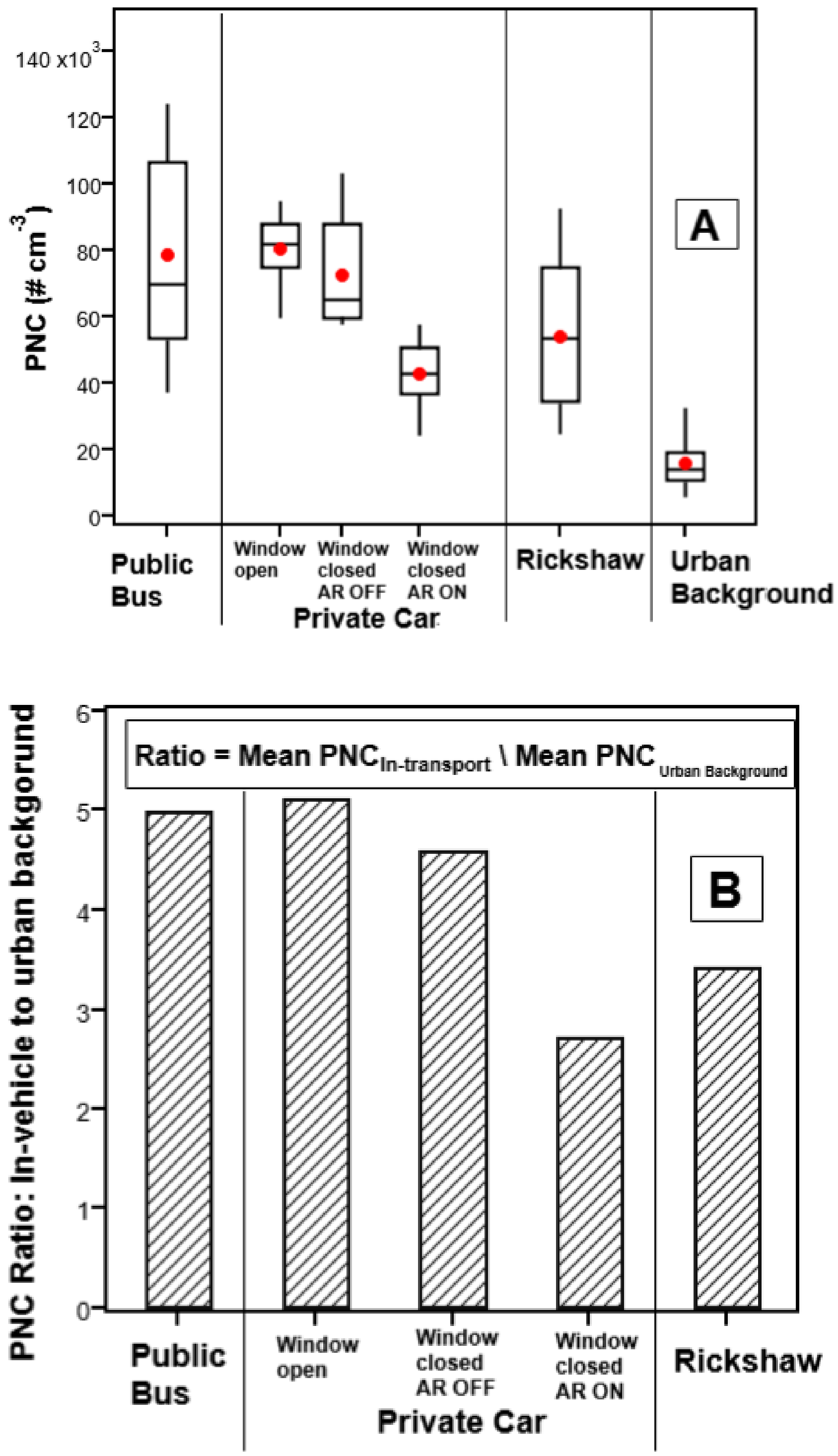

Figure 4.1: (a) Comparison of particle number concentrations (PNC) measured in different transportation modes and an urban background location. (b) Ratio of in-vehicle mean PNC to urban background mean PNC

The average PNC in rickshaw was lower than public bus and private car with window open. It should be noted that the rickshaw measurements were collected on a much-shorted route compared to the public bus and private car (Figure 3.1). Furthermore, rickshaw samplings were not collected covering different parts of a day. Specifically, morning samplings were missing for the rickshaw (Table 4.1). Therefore, a comparison of rickshaw measurement with other sampling modes is difficult.

Figure 4.1 compares in-vehicle PNC with the measurements in an urban background location. In-vehicle PNC in all modes is substantially higher than the urban background level. The PNCs in public bus and car sampling with window-open are about five times of urban background PNC. In-car PNC with the window closed and air recirculation off is 4.5 times of urban background level; under air recirculation on condition, about 3 times of urban background level.

Numerous previous studies reported that on-road/near-road PNC are substantially higher than background PNC.[11] PNC level decays exponentially as one moves away from the roadway edge, and concentration can reduce 2-10 times within a 50-100 m from the roadway edge.[9] This explains the observed large difference between in-vehicle (on-road) and urban background concentrations.

4.3 Temporal Variation of UFP Measured in Different Transportation Modes

Figure 4.2 shows the temporal variations of in-vehicle PNC measured in three different parts of a day (i.e., morning: 8 am-10 am, midday: 11 am - 2 pm, and afternoon: 3 pm – 6 pm). The morning and afternoon samplings overlap with the traffic rush hours. As expected, the measured PNC in a certain transport mode varies with the time of sampling. In general, concentrations are higher in the morning and lower in mid-day and afternoon measurements. This reflects the impact of dynamic diurnal variation of meteorology and traffic conditions on traffic-related air pollution.[68]

Usually, traffics is higher during morning and evening rush hours. During these periods, the ambient concentrations are expected to be higher due to several reasons, such as (i) higher traffic volume, (ii) slow-moving, and more stop/start (acceleration/deceleration) traffic. Ambient concentrations are also higher in the morning due to the lower mixing height. Considering the impact of both meteorology and traffic conditions, ambient concentrations are expected to be highest during morning traffic rush hour. These effects are reflected in the in-vehicle measurements collected at different periods of the day (e.g., morning concentrations are higher, mid-day and afternoon are lower).

In-vehicle PNCs are higher than the urban background level during any part of a day. This implies that in-vehicle exposures will be higher for commuting during any part of a day, but this would be substantially higher for commuting during morning hours, consistent with previous research on dynamic diurnal behavior of PNC[14].

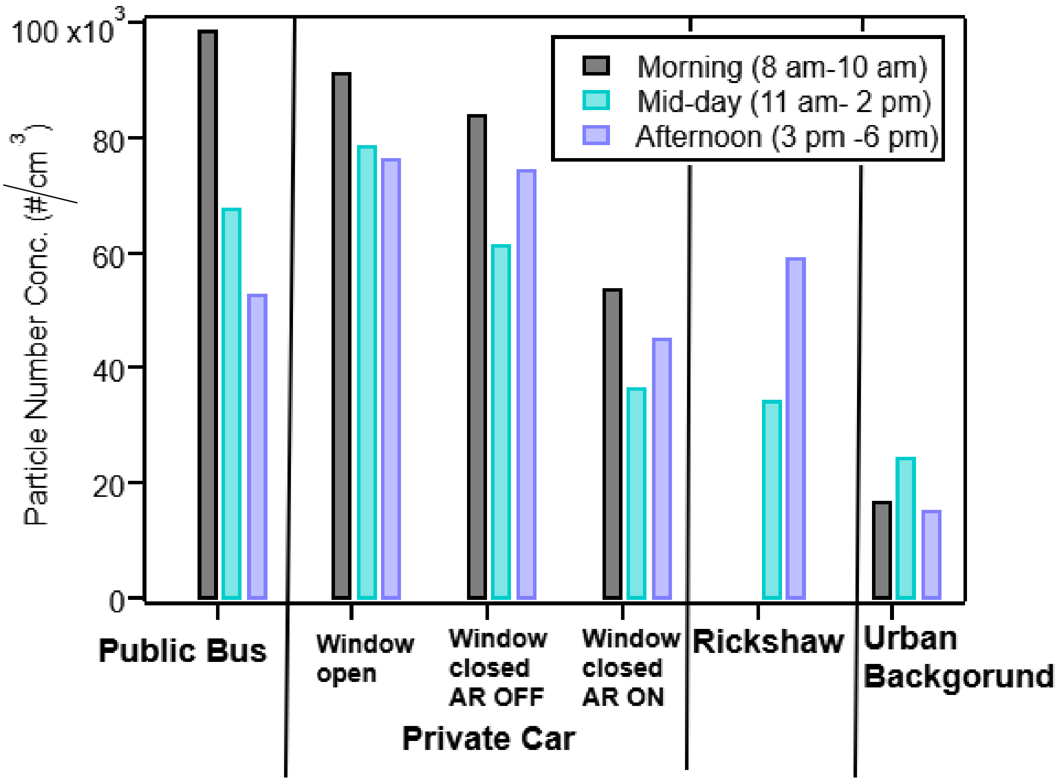

Figure 4.2: Comparison of mean PNCs measured in different transportation modes and an urban background location at different times (i.e., morning, mid-day, afternoon).

4.4 Spatial Variation of UFP Measured in Different Transportation Modes

Figures 4.3 and 4.4 compare the spatial variation of in-vehicle PNC measured in various transportation modes along the sampling route. Figures 4.3 and 4.4 show the average concentrations measured within each 100 m road segment across all sampling days. Results indicate that although the relative difference between sampling modes persists (e.g., PNC in public bus is the highest, car with closed window, and air recirculation ON is the lowest), concentrations vary spatially for a particular mode.

For the public bus and car with an open window, the spatial distributions of in-vehicle PNCs are almost similar (Figure 4.3A, B). This reflects the influence of ambient/on-road spatial variations of PNC. Concentrations spatially vary between 4-8 times of urban background level, relatively higher near the Mirpur area and lower in the Azimpur area. For a car with the window closed and air-recirculation on, in-vehicle concentrations spatially vary between 2-4 times of urban background level.

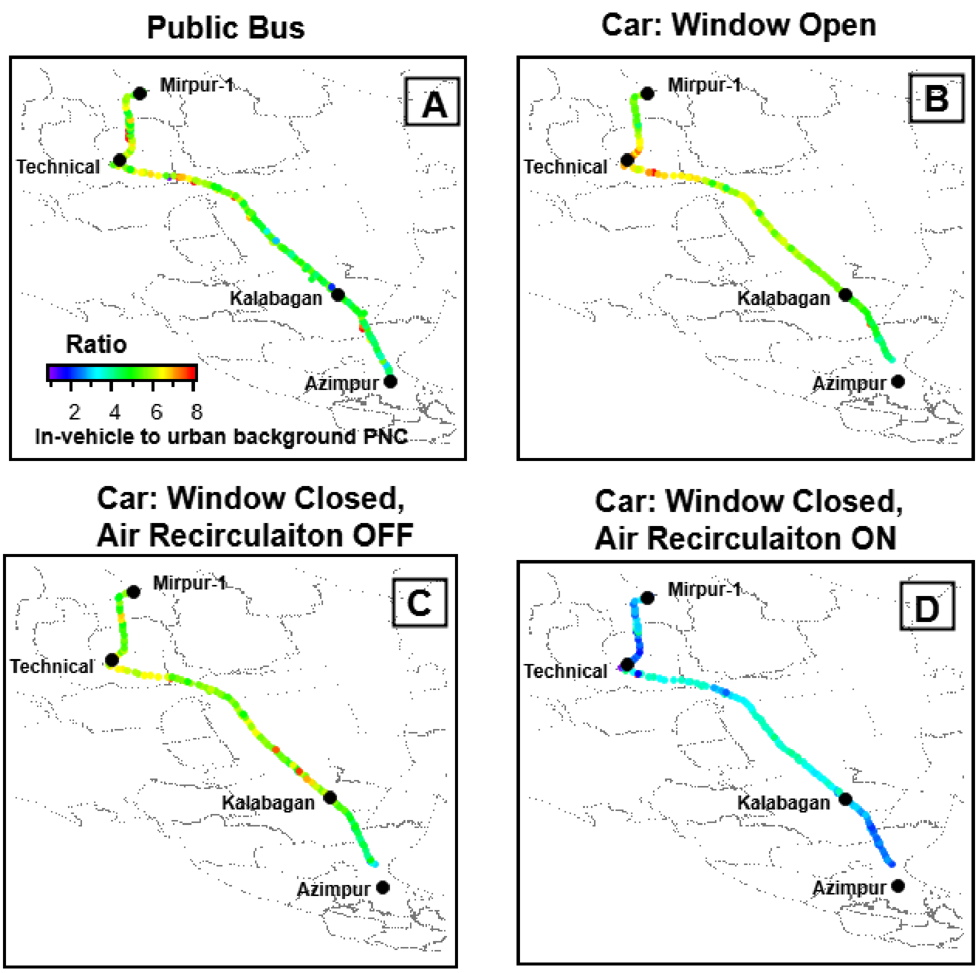

Figure 4.3: Spatial variation of in-vehicle particle number concentrations measured in different transportation modes along the primary sampling route ("Azimpur to Mirpur-1"). In all panels, concentrations are normalized by the mean urban background PNC (i.e., in-vehicle PNC / urban background PNC).

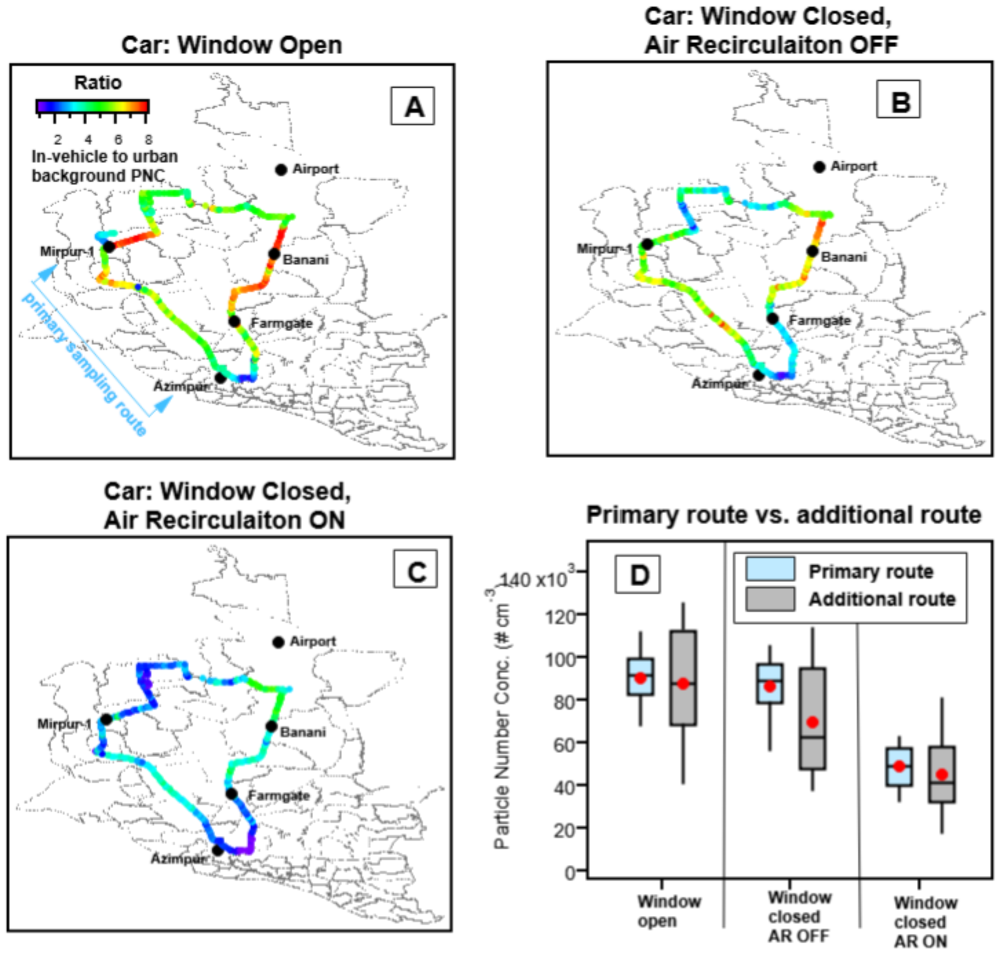

Figure 4.4: (A-C) Comparison of the spatial variation of in-vehicle particle number concentrations in different car sampling modes along the primary and additional routes. Concentrations shown in panels A, B, C are normalized by the mean urban background PNC (i.e., in-vehicle PNC / urban background PNC). (D) Comparison of study-average PNCs in different car sampling modes on primary route versus additional route.

To assess the robustness of findings observed in the selected primary route (Azimpur to Mirpur-1, where most of the data were collected), Figure 4.4 compares these measurements with the data collected on an additional route. This comparison is only performed for different car sampling modes. Results indicate that the trends in vehicle PNCs in different sampling modes are robust. For example, car sampling with open windows measured the highest concentrations for both primary and additional routes, and car sampling with closed windows and air recirculation 'on' measured the lowest concentrations in both routes.

The in-car concentrations with open windows vary between 4-8 times of urban background level for both routes. In-car concentrations with window-closed and air recirculation 'on' vary between 2-4 times of urban background level. The distribution of concentrations from both routes, shown in Figure 4.4D, are also comparable. However, the additional route shows higher variability compared to the selected primary route. This is expected because the length of the additional route is much bigger, and it covers a wide part of the city, covering diverse land- uses. *Appendix-C* provides further details on spatial variations of measured PNC and $PM_{2.5}$ in various transportation modes at the different part of a day on primary and additional routes

4.5 Implications for Exposures

This section examines the exposures relevant implications of measured in-vehicles and urban background PNCs discussed above. Numerous past students have reported that while the commuting time is only a small fraction of the day, they could substantially contribute to the daily air pollution exposures.[19,35,47] Figure 4.5 shows this comparison for the commuters in Dhaka city, Bangladesh. The estimates in Figure 4.5 used the study-mean PNCs in different transportation modes.

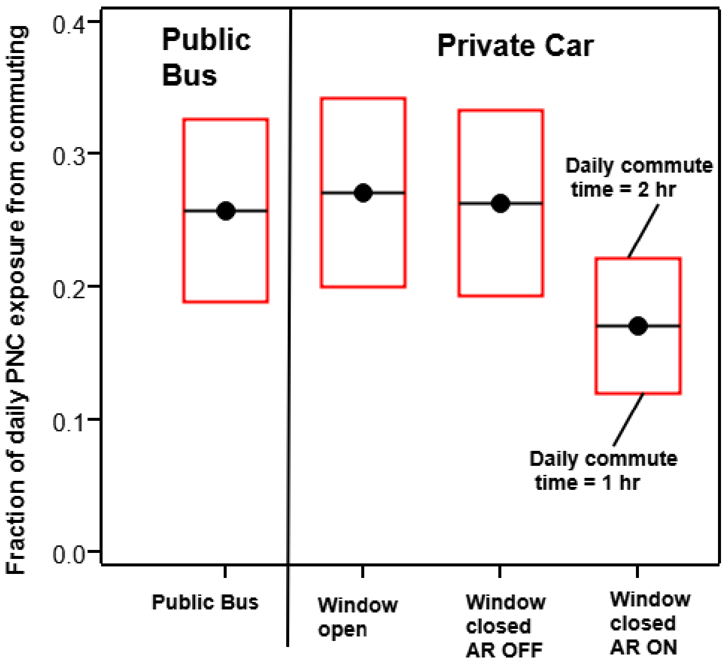

Figure 4.5: Comparison of estimated fraction of daily PNC exposure from commuting in various transportation modes.

Estimates are shown for daily commuting time of 1 hour and 2 hours. A recent Travel Behavior study in Dhaka city[69] reported that the duration of one-way travel to work for most commuters is within 60 minutes (typical range 20 minutes to 120 minutes). Therefore, for both ways commuting, a range of 1-2 hours is a reasonable window. For the rest of the time, exposure concentrations are assumed equal to the mean urban background concentration. Urban outdoor PNC vary spatially. The indoor and outdoor concentrations also vary.[70]

Actual exposures depend on where people spend time and concentrations at those micro-environments. Due to the lack of data availability, such detailed exposure assignments are not possible for the commuters in Dhaka city. However, most of the time, people spend time indoors (either home or office), and an assumption of concentrations at those locations similar to urban background level is a reasonable assumption.

Since in-vehicle PNCs vary across transportation modes, the fraction of daily PNC exposures from commuting varies by transport mode. Estimates in Figure 4.5 shows that 1-2 hours of commute time in Dhaka city contributes ~ 15-35% of daily PNC exposures. Exposures are similar for commuters of public buses, private cars with windows open, private cars with windows closed, and air recirculation off. Exposures are lower for commuters of private cars with windows closed, and air recirculation on.

Figure 4.5 indicates that PNC exposures from commuting are about a factor of two lower for commuters with private cars with windows closed and air recirculation ON, compared to other modes. There is a strong link between transportation modal choice and socioeconomic status of the commuters, and thus, commuting relevant air pollution exposures.[71] Figure 4.6 explores this relationship for the commuters in Dhaka city.

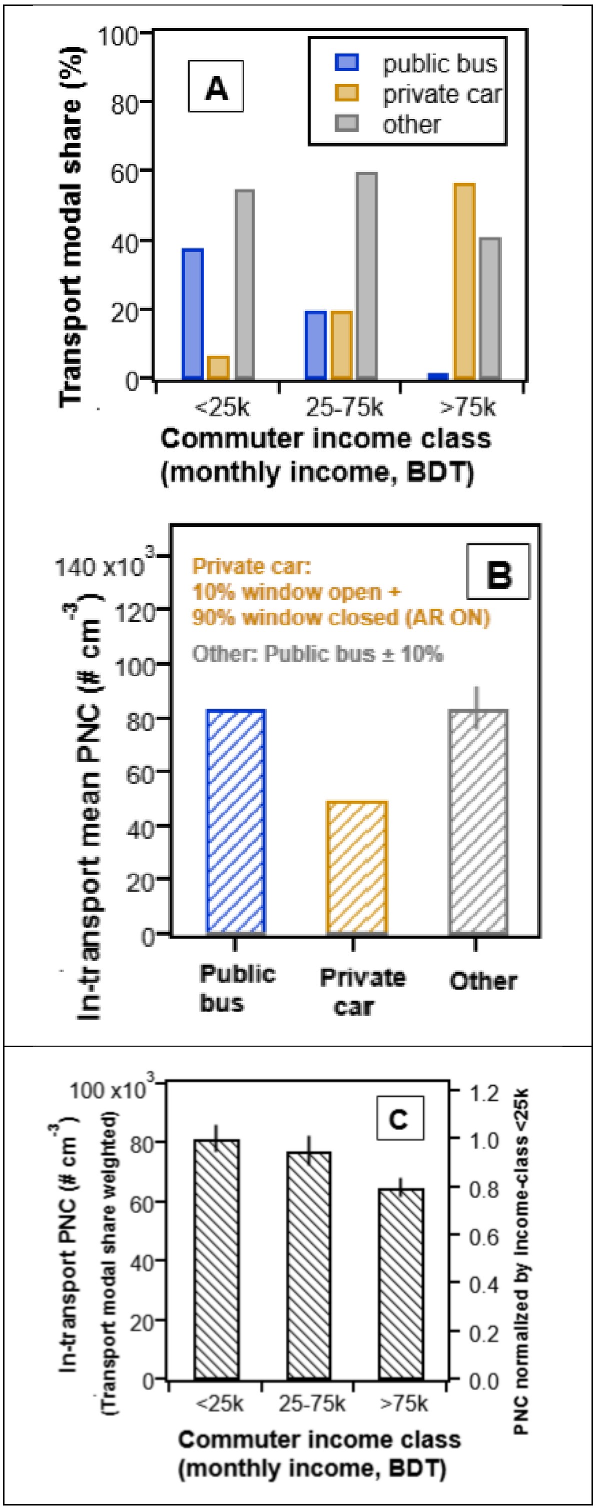

Figure 4.6: Comparison of estimated in-vehicle PNC exposures by commuter income class. A. Distribution of transportation modal share by commuter income class. (B). Average PNC exposures in various transportation modes. (C). Modal share weighted in transport PNC exposures by commuter income class.

A survey was conducted to get the distribution of transportation modal share by socio-economic status of the commuters (e.g., monthly income). A summary of transportation modal choice as a function of demographic and socio-economic variables is given in Appendix-D. Figure 4.6A shows the transportation modal share for three income classes. As expected, the lower-income group (< BDT 25k per month) has a higher share for public bus (~ 40%) and a lower share for private car (5%). On the other hand, the higher-income group (> BDT 75k per month) has a substantially higher share for private car (60%) and lower for the public bus (< 2%). However, more than 50% of commuters across all income classes use transportation other than a public bus or private car, shown as "other" in Figure 4.6A. This "other" includes CNG, Leguna, Motor Bike, Rickshaw, and walking. This is consistent with another recent travel behavior survey in Dhaka city among employees of 20 Small and Medium Enterprises (SMEs) (N = 314, public bus: 44%, Car/Car Share/Office transport: 10%, other: 46%)[69].

Figure 4.6B shows the assigned average in-transport PNC exposures for three modes of transportation (public bus, private car, and other). Since the exposures in a private car strongly depend on window conditions, the average exposure is estimated as the weighted average of two scenarios: window open (10% of the time) and window closed and air recirculation on (90% of the time). The weighting factors are assumed based on local observations.

Typically, in Dhaka city, cars run in window-closed condition. However, the information about air recirculation is mostly unknown. While window closed, the air recirculation on condition is assumed to get maximum achievable exposure contrast between commuters on the car and other modes. Since data were not available for other transportation modes, they are assumed to be within ±10% of public bus. Other transportations modes in Dhaka city are CNG, Leguna, Motor Bike, Rickshaw, and walking. These modes are open/semi-open to ambient conditions, similar to Dhaka city's typical public bus operational condition.

The estimated modal-share weighted PNC exposures for different income groups are shown in Figure. 4.6C As expected, overall exposures are higher for the lower-income group and lower for the higher-income group. On average, exposure for the lower income group (< 25K) is about 20% higher than for the higher income group (> 75K). Similar disparities are reported in past studies worldwide[52,71].

CHAPTER 5
CONCLUSIONS

5.1 Summary of Major Findings

This study measures and compares in-vehicle ultrafine particles (UFP) concentrations in selected transportation modes in Dhaka city, Bangladesh. Transportation modes are: (i) public bus, (ii) private car with windows open, (iii) private car with windows closed and air recirculation OFF, (iv) private car with windows closed and air recirculation ON, and (v) Rickshaw. UFP concentrations are measured as total particle number concentrations (PNC), a commonly used metric for UFP. The major findings are outlined below:

a. In-vehicle PNCs vary by transportation mode, higher in the public bus and private car with open windows and lower in the private car with closed windows and air recirculation on. The inter-modal variations are about a factor of two.
b. In all selected transportation modes, the in-vehicle PNCs are substantially higher than the urban background level. They are about 4-8 times higher in the public bus and private car with open windows and 2-4 times higher in the private car with closed windows and air recirculation on.
c. In-vehicle PNCs vary spatially and temporally. For all selected transportation modes, concentrations are typically higher in the morning than in mid-day and afternoon. Spatial variations (a factor of 2-4) are much larger than temporal variations (a factor of 1.2-1.8).
d. Substantially higher in-vehicle PNCs and their inter-modal variations have implications on PNC personal exposures. About 1-2 hours commuting (4-8% of daily hours) contributes 20-35% of daily PNC exposures. These exposures are higher for public bus commuters and lower for private car commuters, specifically, those who commute with car windows closed and air recirculation on.

5.2 Limitations and Recommendations for Future Study

This study recommends the following scopes for future studies:

a. Although this study has covered the major transportations modes in Dhaka city (private car, public bus, rickshaw), it has not covered all the commonly used transportation modes, such as CNG, Leguna, Motor Bike, and walking. Travel behavior survey indicates that about 50% of commuters in Dhaka city used these other modes for daily commuting. Future studies should measure and compare in-vehicle concentrations in these other transportation modes.

b. Although rickshaw is a widely used transportation mode in Dhaka city, this study has collected limited measurements for the rickshaw. Measurements were collected on a shorted route. No samplings were collected in morning. Therefore, measured PNC in rickshaw may not represent the actual exposures for Rickshaw commuters in Dhaka city. Future studies should collect in-rickshaw exposure measurements on various routes in the city over a diverse set of times covering a different part of the day and seasons.

c. The scope of the study was limited to sampling within Dhaka city. In general, the findings in this study may represent the in-vehicle exposures for commuters in other metropolitan cities in Bangladesh. Future studies should conduct measurements in other cities to assess how this study's findings represent for other cities in Bangladesh.

REFERENCES

(1) HEI. Understanding the Health Effects of Ambient Ultrafine Particles. HEI Perspectives 3. Boston, MA: Health Effects Institute 2013.

(2) Harrison, R. M.; Shi, J. P.; Xi, S.; Khan, A.; Mark, D.; Kinnersley, R.and Yin, J. Measurement of Number, Mass and Size Distribution of Particles in the Atmosphere. *Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci.* 2000, *358* (1775), 2567–2580. https://doi.org/10.1098/rsta.2000.0669.

(3) Kumar, P.; Robins, A.; Vardoulakis, S. and Britter, R. A Review of the Characteristics of Nanoparticles in the Urban Atmosphere and the Prospects for Developing Regulatory Controls. *Atmos. Environ.* 2010, *44* (39), 5035–5052. https://doi.org/10.1016/j.atmosenv.2010.08.016.

(4) Delfino, R. J.; Sioutas, C. and Malik, S. Potential Role of Ultrafine Particles in Associations between Airborne Particle Mass and Cardiovascular Health. *Environ. Health Perspect.* 2005, *113* (8), 934–946.

(5) Li, N.; Sioutas, C.; Cho, A.; Schmitz, D.; Misra, C.; Sempf, J.; Wang, M.; Oberley, T.; Froines, J. and Nel, A. Ultrafine Particulate Pollutants Induce Oxidative Stress and Mitochondrial Damage. *Environ. Health Perspect.* 2003, *111* (4), 455–460.

(6) Nel, A.; Xia, T.; Mädler, L. and Li, N. Toxic Potential of Materials at the Nanolevel. *Science* 2006, *311* (5761), 622–627. https://doi.org/10.1126/science.1114397.

(7) Salma, I.; Füri, P.; Németh, Z.; Balásházy, I.; Hofmann, W. and Farkas, Á. Lung Burden and Deposition Distribution of Inhaled Atmospheric Urban Ultrafine Particles as the First Step in Their Health Risk Assessment.*Atmos. Environ.* 2015, *104* (Supplement C), 39–49. https://doi.org/10.1016/j.atmosenv.2014.12.060.

(8) Schmid, O.; Möller, W.; Semmler-Behnke, M.; Ferron, G. A.; Karg, E.; Lipka, J.; Schulz, H.; Kreyling, W. G. and Stoeger, T. Dosimetry and Toxicology of Inhaled Ultrafine Particles. *Biomark. Biochem. Indic. Expo. Response Susceptibility Chem.* 2009, *14 Suppl 1*, 67–73. https://doi.org/10.1080/13547500902965617.

(9) Karner, A. A.; Eisinger, D. S. and Niemeier, D. A. Near-Roadway Air Quality: Synthesizing the Findings from Real-World Data. *Environ. Sci. Technol.* 2010, *44* (14), 5334–5344. https://doi.org/10.1021/es100008x.

(10) Saha, P. K.; Khlystov, A. and Grieshop, A. P. Downwind Evolution of the Volatility and Mixing State of Near-Road Aerosols near a US Interstate Highway. *Atmos Chem Phys* 2018, *18* (3), 2139–2154. https://doi.org/10.5194/acp-18-2139-2018.

(11) Zhang, K. M.; Wexler, A. S.; Zhu, Y. F.; Hinds, W. C. and Sioutas, C. Evolution of Particle Number Distribution near Roadways. Part II: The 'Road-to-Ambient' Process. *Atmos. Environ.* 2004, *38* (38), 6655–6665. https://doi.org/10.1016/j.atmosenv.2004.06.044.

(12) Kumar, P.; Morawska, L.; Birmili, W.; Paasonen, P.; Hu, M.; Kulmala, M.; Harrison, R. M.; Norford, L. and Britter, R. Ultrafine Particles in Cities. *Environ. Int.* 2014, *66*, 1–10. https://doi.org/10.1016/j.envint.2014.01.013.

(13) Moore, K.; Krudysz, M.; Pakbin, P.; Hudda, N. and Sioutas, C. Intra-Community Variability in Total Particle Number Concentrations in the San Pedro Harbor Area (Los Angeles, California). *Aerosol Sci. Technol.* 2009, *43* (6), 587–603. https://doi.org/10.1080/02786820902800900.

(14) Saha, P. K.; Khlystov, A.; Snyder, M. G. and Grieshop, A. P. Characterization of Air Pollutant Concentrations, Fleet Emission Factors, and Dispersion near a North Carolina Interstate Freeway across Two Seasons. *Atmos. Environ.* 2018, *177*, 143–153. https://doi.org/10.1016/j.atmosenv.2018.01.019.

(15) Saha, P. K.; Zimmerman, N.; Malings, C.; Hauryliuk, A.; Li, Z.; Snell, L.; Subramanian, R.; Lipsky, E.; Apte, J. S.; Robinson, A. L. and Presto, A. A. Quantifying High-Resolution Spatial Variations and Local Source Impacts of Urban Ultrafine Particle Concentrations. *Sci. Total Environ.* 2019, *655*, 473–481. https://doi.org/10.1016/j.scitotenv.2018.11.197.

(16) Baldauf, R. W.; Devlin, R. B.; Gehr, P.; Giannelli, R.; Hassett-Sipple, B.; Jung, H.; Martini, G.; McDonald, J.; Sacks, J. D. and Walker, K. Ultrafine Particle Metrics and Research Considerations: Review of the 2015 UFP Workshop. *Int. J. Environ. Res. Public. Health* 2016, *13* (11). https://doi.org/10.3390/ijerph13111054.

(17) Begum, B. A. and Hopke, P. K. Ambient Air Quality in Dhaka Bangladesh over Two Decades: Impacts of Policy on Air Quality. *Aerosol Air Qual. Res.* 2018, *18* (7), 1910–1920. https://doi.org/10.4209/aaqr.2017.11.0465.

(18) HEI. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects. Special Report 17, Health Effects Institute, Boston, Massachusetts 2010.

(19) Zhu, Y.; Eiguren-Fernandez, A.; Hinds, W. C. and Miguel, A. H. In-Cabin Commuter Exposure to Ultrafine Particles on Los Angeles Freeways. *Environ. Sci. Technol.* 2007, *41* (7), 2138–2145. https://doi.org/10.1021/es0618797.

(20) Fruin, S.; Westerdahl, D.; Sax, T. and Sioutas, C.; Fine, P. M. Measurements and Predictors of On-Road Ultrafine Particle Concentrations and Associated Pollutants in Los Angeles. *Atmos. Environ.* 2008, *42* (2), 207–219. https://doi.org/10.1016/j.atmosenv.2007.09.057.

(21) Siddique, Md. A. B. and Choudhury, C. F. Modelling the Behavioural Response to Congestion Pricing in Dhaka, Bangladesh. *Transp. Dev. Econ.* 2017, *3* (2), 23. https://doi.org/10.1007/s40890-017-0052-y.

(22) Nguyen, N. P. and Marshall, J. D. Impact, Efficiency, Inequality, and Injustice of Urban Air Pollution: Variability by Emission Location. *Environ. Res. Lett.* 2018, *13* (2), 024002. https://doi.org/10.1088/1748-9326/aa9cb5.

(23) Seinfeld, J. H. and Pandis, S. N. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*, 2nd Edition.; John Wiley & Sons: New York, 2006.

(24) Araujo, J. A. and Nel, A. E. Particulate Matter and Atherosclerosis: Role of Particle Size, Composition and Oxidative Stress. *Part. Fibre Toxicol.* 2009, *6* (1), 24. https://doi.org/10.1186/1743-8977-6-24.

(25) Rivas, I.; Beddows, D. C. S.; Amato, F.; Green, D. C.; Järvi, L.; Hueglin, C.; Reche, C.; Timonen, H.; Fuller, G. W.; Niemi, J. V.; Pérez, N.; Aurela, M.; Hopke, P. K.; Alastuey, A.; Kulmala, M.; Harrison, R. M.; Querol, X. and Kelly, F. J. Source Apportionment of Particle Number Size Distribution in Urban Background and Traffic Stations in Four European Cities. *Environ. Int.* 2020, *135*, 105345. https://doi.org/10.1016/j.envint.2019.105345.

(26) Kwon, H.-S.; Ryu, M. H. and Carlsten, C. Ultrafine Particles: Unique Physicochemical Properties Relevant to Health and Disease. *Exp. Mol. Med.* 2020, *52* (3), 318–328. https://doi.org/10.1038/s12276-020-0405-1.

(27) Chen, R.; Hu, B.; Liu, Y.; Xu, J.; Yang, G.; Xu, D. and Chen, C. Beyond PM2.5: The Role of Ultrafine Particles on Adverse Health Effects of Air Pollution. *Biochim. Biophys. Acta BBA - Gen. Subj.* 2016, *1860* (12), 2844–2855. https://doi.org/10.1016/j.bbagen.2016.03.019.

(28) Sowlat, M. H.; Hasheminassab, S. and Sioutas, C. Source Apportionment of Ambient Particle Number Concentrations in Central Los Angeles Using Positive Matrix Factorization (PMF). *Atmospheric Chem. Phys.* 2016, *16* (8), 4849–4866. https://doi.org/10.5194/acp-16-4849-2016.

(29) Posner, L. N. and Pandis, S. N. Sources of Ultrafine Particles in the Eastern United States. *Atmos. Environ.* 2015, *111*, 103–112. https://doi.org/10.1016/j.atmosenv.2015.03.033.

(30) Brines, M.; Dall'Osto, M.; Beddows, D. C. S.; Harrison, R. M.; Gómez-Moreno, F.; Núñez, L.; Artíñano, B.; Costabile, F.; Gobbi, G. P.; Salimi, F.; Morawska, L.; Sioutas, C. and Querol, X. Traffic and Nucleation Events as Main Sources of Ultrafine Particles in High-Insolation Developed World Cities. *Atmospheric Chem. Phys.* 2015, *15* (10), 5929–5945. https://doi.org/10.5194/acp-15-5929-2015.

(31) Yu, X.; Venecek, M. A.; Hu, J.; Tanrikulu, S.; Soon, S.-T.; Tran, C.; Fairley, D. and Kleeman, M. J. Sources of Airborne Ultrafine Particle Number and Mass Concentrations in California. *Atmos Chem Phys Discuss* 2018. https://doi.org/10.5194/acp-2018-832.

(32) Hudda, N.; Simon, M. C.; Zamore, W. and Durant, J. L. Aviation-Related Impacts on Ultrafine Particle Number Concentrations Outside and Inside Residences near an Airport. *Environ. Sci. Technol.* 2018, *52* (4), 1765–1772. https://doi.org/10.1021/acs.est.7b05593.

(33) Kulmala, M.; Petäjä, T.; Nieminen, T.; Sipilä, M.; Manninen, H. E.; Lehtipalo, K.; Dal Maso, M.; Aalto, P. P.; Junninen, H.; Paasonen, P.; Riipinen, I.; Lehtinen, K. E. J.; Laaksonen, A. and Kerminen, V.-M. Measurement of the Nucleation of Atmospheric Aerosol Particles. *Nat. Protoc.* 2012, *7* (9), 1651–1667. https://doi.org/10.1038/nprot.2012.091.

(34) Zhu, Y.; Hinds, W. C.; Kim, S.; Shen, S. and Sioutas, C. Study of Ultrafine Particles near a Major Highway with Heavy-Duty Diesel Traffic. *Atmos. Environ.* 2002, *36* (27), 4323–4335. https://doi.org/10.1016/S1352-2310(02)00354-0.

(35) Fruin, S.; Westerdahl, D.; Sax, T. and Sioutas, C.Fine, P. M. Measurements and Predictors of On-Road Ultrafine Particle Concentrations and Associated Pollutants in Los Angeles. *Atmos. Environ.* 2008, *42* (2), 207–219. https://doi.org/10.1016/j.atmosenv.2007.09.057.

(36) Hudda, N.; Eckel, S. P.; Knibbs, L. D.; Sioutas, C.; Delfino, R. J. and Fruin, S. A. Linking In-Vehicle Ultrafine Particle Exposures to On-Road Concentrations. *Atmospheric Environ. Oxf. Engl. 1994* 2012, *59*, 578–586. https://doi.org/10.1016/j.atmosenv.2012.05.021.

(37) Miao, Q.; Bouchard, M.; Chen, D.; Rosenberg, M. W. and Aronson, K. J. Commuting Behaviors and Exposure to Air Pollution in Montreal, Canada. *Sci. Total Environ.* 2015, *508*, 193–198. https://doi.org/10.1016/j.scitotenv.2014.11.078.

(38) Yang, F.; Kaul, D.; Wong, K. C.; Westerdahl, D.; Sun, L.; Ho, K.; Tian, L.; Brimblecombe, P. and Ning, Z. Heterogeneity of Passenger Exposure to Air Pollutants in Public Transport Microenvironments. *Atmos. Environ.* 2015, *109*, 42–51. https://doi.org/10.1016/j.atmosenv.2015.03.009.

(39) Nazelle, A.; Fruin, S.; Westerdahl, D.; Martinez, D.; Ripoll, A.; Kubesch, N. and Nieuwenhuijsen, M. A Travel Mode Comparison of Commuters' Exposures to Air Pollutants in Barcelona. *Atmos. Environ.* 2012, *59*, 151–159. https://doi.org/10.1016/j.atmosenv.2012.05.013.

(40) Rim, D.; Siegel, J.; Spinhirne, J.; Webb, A. and McDonald-Buller, E. Characteristics of Cabin Air Quality in School Buses in Central Texas. *Atmos. Environ.* 2008, *42* (26), 6453–6464. https://doi.org/10.1016/j.atmosenv.2008.04.030.

(41) Quiros, D. C.; Lee, E. S.; Wang, R. and Zhu, Y. Ultrafine Particle Exposures While Walking, Cycling, and Driving along an Urban Residential Roadway. *Atmos. Environ.* 2013, *73*, 185–194. https://doi.org/10.1016/j.atmosenv.2013.03.027.

(42) Zhou, Y.; Shao, Y.; Yuan, Y.; Liu, J.; Zou, X.; Bai, P.; Zhan, M.; Zhang, P.; Vlaanderen, J. and Vermeulen, R.; Downward, G. S. Personal Black Carbon and Ultrafine Particles Exposures among High School Students in Urban China. *Environ. Pollut.* 2020, *265*, 114825. https://doi.org/10.1016/j.envpol.2020.114825.

(43) Onat, B.; Şahin, Ü. A.; Uzun, B.; Akın, Ö.; Özkaya, F. and Ayvaz, C. Determinants of Exposure to Ultrafine Particulate Matter, Black Carbon, and PM2.5 in Common Travel Modes in Istanbul. *Atmos. Environ.* 2019, *206*, 258–270. https://doi.org/10.1016/j.atmosenv.2019.02.015.

(44) Goel, A. and Kumar, P. Characterisation of Nanoparticle Emissions and Exposure at Traffic Intersections through Fast–Response Mobile and Sequential Measurements. *Atmos. Environ.* 2015, *107*, 374–390. https://doi.org/10.1016/j.atmosenv.2015.02.002.

(45) Hertel, O.; Hvidberg, M.; Ketzel, M.; Storm, L. and Stausgaard, L. A Proper Choice of Route Significantly Reduces Air Pollution Exposure--a Study on Bicycle and Bus Trips in Urban Streets. *Sci. Total Environ.* 2008, *389* (1), 58–70. https://doi.org/10.1016/j.scitotenv.2007.08.058.

(46) Li, X.; Chen, X.; Yuan, X.; Zeng, G.; León, T.; Liang, J.; Chen, G. and Yuan, X. Characteristics of Particulate Pollution (PM2.5 and PM10) and Their Spacescale-Dependent Relationships with Meteorological Elements in China. *Sustainability* 2017, *9* (12), 2330. https://doi.org/10.3390/su9122330.

(47) Kumar, P.; Hama, S.; Nogueira, T.; Abbass, R. A.; Brand, V. S.; Andrade, M. de F.; Asfaw, A.; Aziz, K. H.; Cao, S.-J.; El-Gendy, A.; Islam, S.; Jeba, F.; Khare, M.; Mamuya, S. H.; Martinez, J.; Meng, M.-R.; Morawska, L.; Muula, A. S.; Shiva Nagendra, S. M.; Ngowi, A. V.; Omer, K.; Olaya, Y.; Osano, P. and Salam, A. In-Car Particulate Matter Exposure across Ten Global Cities. *Sci. Total Environ.* 2021, *750*, 141395. https://doi.org/10.1016/j.scitotenv.2020.141395.

(48) Ham, W.; Vijayan, A.; Schulte, N. and Herner, J. D. Commuter Exposure to PM2.5, BC, and UFP in Six Common Transport Microenvironments in Sacramento, California. *Atmos. Environ.* 2017, *167*, 335–345. https://doi.org/10.1016/j.atmosenv.2017.08.024.

(49) Hajat, A.;Hsia, C. and O'Neill, M. S. Socioeconomic Disparities and Air Pollution Exposure: A Global Review. *Curr. Environ. Health Rep.* 2015, *2* (4), 440–450. https://doi.org/10.1007/s40572-015-0069-5.

(50) Clark, L. P.; Millet, D. B. and Marshall, J. D. National Patterns in Environmental Injustice and Inequality: Outdoor NO2 Air Pollution in the United States. *PLOS ONE* 2014, *9* (4), e94431. https://doi.org/10.1371/journal.pone.0094431.

(51) Rivas, I.; Kumar, P. and Hagen-Zanker, A. Exposure to Air Pollutants during Commuting in London: Are There Inequalities among Different Socio-Economic Groups? *Environ. Int.* 2017, *101*, 143–157. https://doi.org/10.1016/j.envint.2017.01.019.

(52) Pratt, G. C.; Vadali, M. L.; Kvale, D. L. and Ellickson, K. M. Traffic, Air Pollution, Minority and Socio-Economic Status: Addressing Inequities in Exposure and Risk. *Int. J. Environ. Res. Public. Health* 2015, *12* (5), 5355–5372. https://doi.org/10.3390/ijerph120505355.

(53) Jephcote, C.; Chen, H. and Ropkins, K. Implementation of the Polluter-Pays Principle (PPP) in Local Transport Policy. *J. Transp. Geogr.* 2016, *55* (C), 58–71.

(54) Donaldson, K.; Brown, D.; Clouter, A.; Duffin, R.; MacNee, W.; Renwick, L.; Tran, L. and Stone, V. The Pulmonary Toxicology of Ultrafine Particles. *J. Aerosol Med. Off. J. Int. Soc. Aerosols Med.* 2002, *15* (2), 213–220. https://doi.org/10.1089/089426802320282338.

(55) Phalen, R. F. The Particulate Air Pollution Controversy. *Nonlinearity Biol. Toxicol. Med.* 2004, *2* (4), 15401420490900244. https://doi.org/10.1080/15401420490900245.

(56) Heal, M. R.;Kumar, P. and Harrison, R. M. Particles, Air Quality, Policy and Health. *Chem. Soc. Rev.* 2012, *41* (19), 6606–6630. https://doi.org/10.1039/c2cs35076a.

(57) Cassee, F. R.; Héroux, M.-E.; Gerlofs-Nijland, M. E. and Kelly, F. J. Particulate Matter beyond Mass: Recent Health Evidence on the Role of Fractions, Chemical Constituents and Sources of Emission. *Inhal. Toxicol.* 2013, *25* (14), 802–812. https://doi.org/10.3109/08958378.2013.850127.

(58) Ohlwein, S.; Kappeler, R.; Kutlar Joss, M.; Künzli, N. and Hoffmann, B. Health Effects of Ultrafine Particles: A Systematic Literature Review Update of Epidemiological Evidence. *Int. J. Public Health* 2019, *64* (4), 547–559. https://doi.org/10.1007/s00038-019-01202-7.

(59) Peters, A.; Rückerl, R. and Cyrys, J. Lessons from Air Pollution Epidemiology for Studies of Engineered Nanomaterials. *J. Occup. Environ. Med.* 2011, *53* (6 Suppl), S8–S13. https://doi.org/10.1097/JOM.0b013e31821ad5c0.

(60) Rouf, M. A.; Nasiruddin, M.; Hossain, A. M. S. and Islam, M. S. Trend of Particulate Matter PM 2.5 and PM 10 in Dhaka City. *Bangladesh J. Sci. Ind. Res.* 2011, *46* (3), 389–398. https://doi.org/10.3329/bjsir.v46i3.9049.

(61) Begum, B. A.; Hopke, P. K. and Markwitz, A. Air Pollution by Fine Particulate Matter in Bangladesh. *Atmospheric Pollut. Res.* 2013, *4* (1), 75–86. https://doi.org/10.5094/APR.2013.008.

(62) Salam, A.; Bauer, H.; Kassin, K.; Mohammad Ullah, S. and Puxbaum, H. Aerosol Chemical Characteristics of a Mega-City in Southeast Asia (Dhaka–Bangladesh). *Atmos. Environ.* 2003, *37* (18), 2517–2528. https://doi.org/10.1016/S1352-2310(03)00135-3.

(63) Salam, A.; Hossain, T.; Siddique, M. N. A. and Alam, A. M. S. Characteristics of Atmospheric Trace Gases, Particulate Matter, and Heavy Metal Pollution in Dhaka, Bangladesh. *Air Qual. Atmosphere Health* 2008, *1* (2), 101. https://doi.org/10.1007/s11869-008-0017-8.

(64) Weagle, C. L.; Snider, G.; Li, C.; van Donkelaar, A.; Philip, S.; Bissonnette, P.; Burke, J.; Jackson, J.; Latimer, R.; Stone, E.; Abboud, I.; Akoshile, C.; Anh, N. X.; Brook, J. R.; Cohen, A.; Dong, J.; Gibson, M. D.; Griffith, D.; He, K. B.; Holben, B. N.; Kahn, R.; Keller, C. A.; Kim, J. S.; Lagrosas, N.; Lestari, P.; Khian, Y. L.; Liu, Y.; Marais, E. A.; Martins, J. V.; Misra, A.; Muliane, U.; Pratiwi, R.; Quel, E. J.; Salam, A.; Segev, L.; Tripathi, S. N.; Wang, C.; Zhang, Q.; Brauer, M.; Rudich, Y. and Martin, R. V. Global Sources of Fine Particulate Matter: Interpretation of PM2.5 Chemical Composition Observed by SPARTAN Using a Global Chemical Transport Model. *Environ. Sci. Technol.* 2018, *52* (20), 11670–11681. https://doi.org/10.1021/acs.est.8b01658.

(65) Hering, S. V.; Spielman, S. R. and Lewis, G. S. Moderated, Water-Based, Condensational Particle Growth in a Laminar Flow. *Aerosol Sci. Technol.* 2014, *48* (4), 401–408. https://doi.org/10.1080/02786826.2014.881460.

(66) Zimmerman, N.; Presto, A. A.; Kumar, S. P. N.; Gu, J.; Hauryliuk, A.; Robinson, E. S.; Robinson, A. L. and R. Subramanian. A Machine Learning Calibration Model Using Random Forests to Improve Sensor Performance for Lower-Cost Air Quality Monitoring. *Atmos Meas Tech* 2018, *11* (1), 291–313. https://doi.org/10.5194/amt-11-291-2018.

(67) Kothari. *Research Methodology: Methods and Techniques.*; New Age International, 2009.

(68) Baldauf, R.; Thoma, E.; Hays, M.; Shores, R.; Kinsey, J.; Gullett, B.; Kimbrough, S.; Isakov, V.; Long, T.; Snow, R.; Khlystov, A.; Weinstein, J.; Chen, F.-L.; Seila, R.; Olson, D.; Gilmour, I.; Cho, S.-H.; Watkins, N.; Rowley, P. and Bang, J. Traffic and Meteorological Impacts on Near-Road Air Quality: Summary of Methods and Trends from the Raleigh Near-Road Study. *J. Air Waste Manag. Assoc.* 2008, *58* (7), 865–878. https://doi.org/10.3155/1047-3289.58.7.865.

(69) Abedin, N.; Rahman, M. M.; Hossain, M. I.; Hisazumi, K. and Ahmed, A. Travel Behavior of SME Employees in Their Work Commute in Emerging Cities: A Case Study in Dhaka City, Bangladesh. *Sustainability* 2020, *12* (24), 1–16.

(70) Meier, R.; Eeftens, M.; Phuleria, H. C.; Ineichen, A.; Corradi, E.; Davey, M.; Fierz, M.; Ducret-Stich, R. E.; Aguilera, I.; Schindler, C.; Rochat, T.; Probst-Hensch, N.; Tsai, M.-Y. and Künzli, N. Differences in Indoor versus Outdoor Concentrations of Ultrafine Particles, PM2.5, PMabsorbance and NO2 in Swiss Homes. *J. Expo. Sci. Environ. Epidemiol.* 2015, *25* (5), 499–505. https://doi.org/10.1038/jes.2015.3.

(71) Rivas, I.; Kumar, P. and Hagen-Zanker, A. Exposure to Air Pollutants during Commuting in London: Are There Inequalities among Different Socio-Economic Groups? *Environ. Int.* 2017, *101*, 143–157. https://doi.org/10.1016/j.envint.2017.01.019.

Appendix

APPENDIX-A: Questionnaire Survey for Transportation Modal Choice and Socio-economic Status of Commuters in Dhaka City

A survey is conducted to characterize air pollution exposure in different transportation modes in Dhaka city. This survey is aimed at finding your exposure to ultrafine particles and other air pollutants and their adverse effects on your health. This survey will take only 5 minutes and your responses are completely anonymous. Thank you in advance for your response. For any questions, please contact

1) Do you live/work/commute in Dhaka city? (If you live/work/commute outside the Dhaka city then the rest of the questionnaire is invalid for you)

☐ Yes
☐ No

2) Gender

☐ Female
☐ Male

3) Age

☐ Less than 15 years
☐ 15-25 years
☐ 25-35 years
☐ 35-45 years
☐ 45-55 years
☐ Above 55 years

4) Education

☐ School Completed (S.S.C)
☐ College Completed (H.S.C)
☐ Bachelor ongoing.
☐ Bachelor's degree (Honors)
☐ Master's degree or above.

5) Income Status

☐ Less than 25,000 taka per month
☐ 25,000-50000 taka per month
☐ 50,000-75,000 taka per month
☐ 75,000-1,00,000 taka per month
☐ More than 1,00,000 taka per month

6) Which mode of transportation do you use most frequently for commuting in Dhaka city?

☐ Public bus
☐ Private car
☐ Rickshaw
☐ Motor cycle
☐ CNG
☐ Leguna

☐ Walking
☐ Cycle

7) How long does it usually take to reach your work/study/business place in the morning?

☐ 0-15 minutes
☐ 15-30 minutes
☐ 30-45 minutes
☐ 45-60 minutes
☐ 1-1:15 h
☐ 1:15-1:30 h
☐ 1:30-1:45 h
☐ 1:45-2:00 h
☐ More Than Two Hours.

8) How long does it usually take to return home in the evening?

☐ less than 15 minutes
☐ 15-30 minutes
☐ 30-45 minutes
☐ 45-60 minutes
☐ 1-1:15 h
☐ 1:15-1:30 h
☐ 1:30-1:45 h
☐ 1:45-2:00 h
☐ More Than Two Hours.

9) Do you own a car?

☐ Yes
☐ No, but I use one provided by my office.
☐ No

10) How would you rate your exposure to dust/air pollution?

☐ Very low
☐ Low
☐ Medium
☐ High
☐ Very high.

APPENDIX-B: Comparison of PNC and $PM_{2.5}$ measured in various transportation modes at different part of the day on primary and additional routes

Table B.1: Average UFP and $PM_{2.5}$ concentrations in various transportation modes in different times of the day.

Time of Day	Average trip time (minutes)	Number of sampling days	PNC (#/cm³) Mean ± SD			$PM_{2.5}$ (µg/m³) Mean ± SD		
Public Bus								
Morning	83	5	97000	±	32000	190	±	60
Midday	85	3	62000	±	27000	210	±	90
Afternoon	63	2	55000	±	19000	90	±	30
Rickshaw								
Morning	53	2	42000	±	16000	70	±	50
Midday	37	5	59000	±	31000	80	±	20
Afternoon	51	3	54000	±	23000	160	±	50
Private Car: Window Open								
Morning	52	4	78000	±	29000	160	±	90
Midday	68	3	77000	±	35000	210	±	80
Afternoon	98	3	73000	±	23000	130	±	70
Private Car: Window Closed, Air Recirculation OFF								
Morning	77	4	63000	±	37000	180	±	90
Midday	87	3	56000	±	25000	110	±	40
Afternoon	74	3	70000	±	42000	140	±	70
Private Car: Window Closed, Air Recirculation ON								
Morning	72	3	48000	±	23000	60	±	20
Midday	77	4	31000	±	13000	60	±	50
Afternoon	68	3	46000	±	22000	100	±	40

Table B.2: Summary of Average UFP and $PM_{2.5}$ concentrations in measured in additional route.

Modes and Conditions	Number of Sampling Days	PNC (#/cm³) Mean ± SD	$PM_{2.5}$ (µg/m³) Mean ± SD /m³)
Private Car: Window Open	3	85000 ± 31000	140 ± 60
Private Car: Window Closed, Air Recirculation OFF	3	60000 ± 28000	130 ± 50
Private Car: Window Closed, Air Recirculation ON	3	42000 ± 21000	70 ± 30

Table B.3: Summary Average PNC and $PM_{2.5}$ concentrations measured in various conditions on additional route in different times of the day.

Time	Number of Sampling Days	PNC (#/cm³) Mean ± SD			$PM_{2.5}$ (μg/m³) Mean ± SD /m³)		
Private Car: Window Open							
Morning	1	94000	±	30000	180	±	50
Midday	1	83000	±	26000	180	±	40
Afternoon	1	80000	±	33000	100	±	40
Private Car: Window Closed, Air Recirculation OFF							
Morning	1	55000	±	24000	100	±	50
Midday	1	57000	±	37000	120	±	20
Afternoon	1	68000	±	23000	60	±	30
Private Car: Window Closed, Air Recirculation ON							
Morning	1	50000	±	28000	60	±	20
Midday	1	40000	±	20000	170	±	20
Afternoon	1	40000	±	17000	80	±	30

APPENDIX- C: Average spatial variations of measured PNC and $PM_{2.5}$ in various transportation modes at different part of a day on primary and additional routes

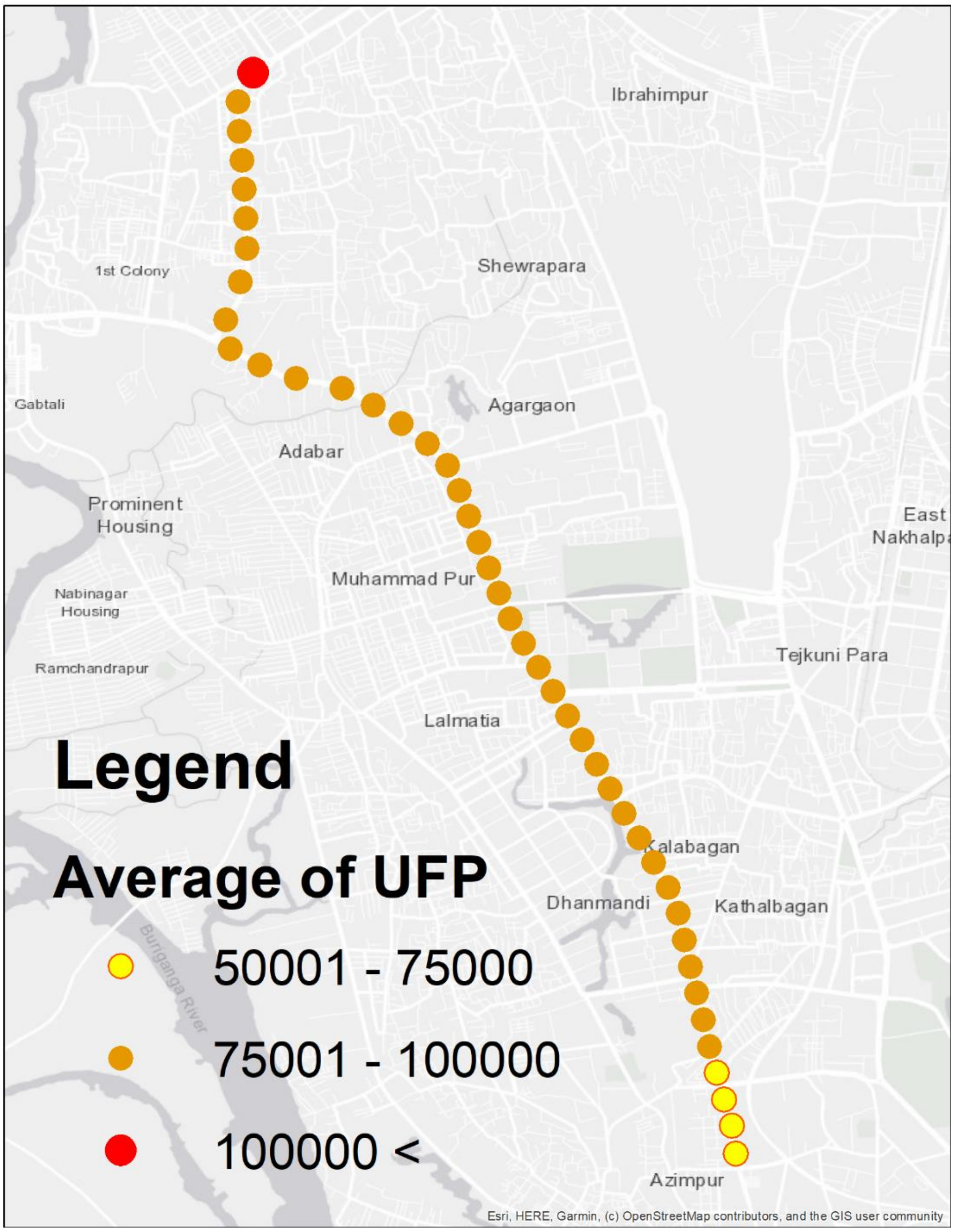

Figure C.1: Spatial variation of in-vehicle PNC measured in Bus along the primary sampling route (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all sampling days.

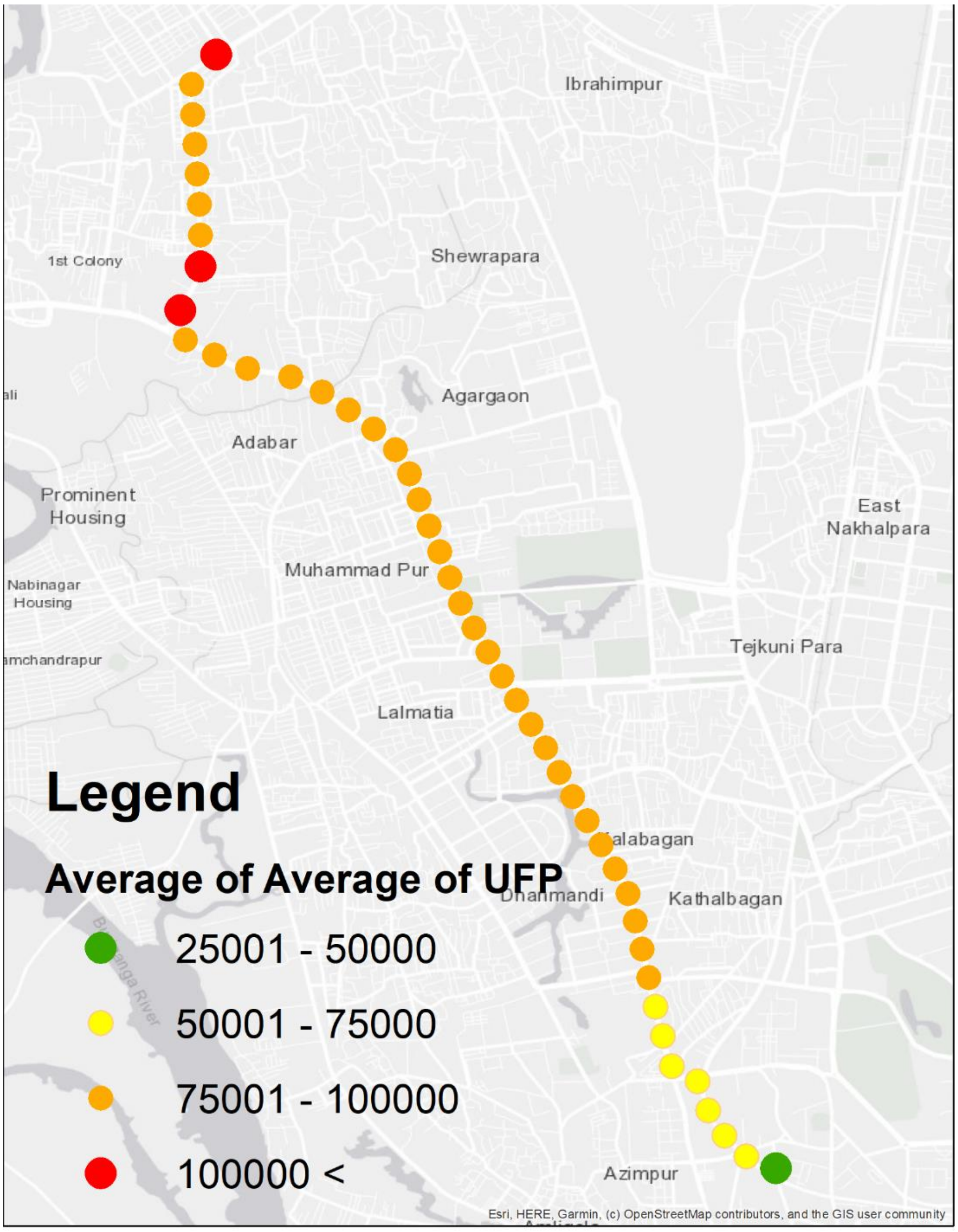

Figure C.2: Spatial variation of in-vehicle PNC measured in Private Car (Window Open) along the primary sampling route (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all sampling days.

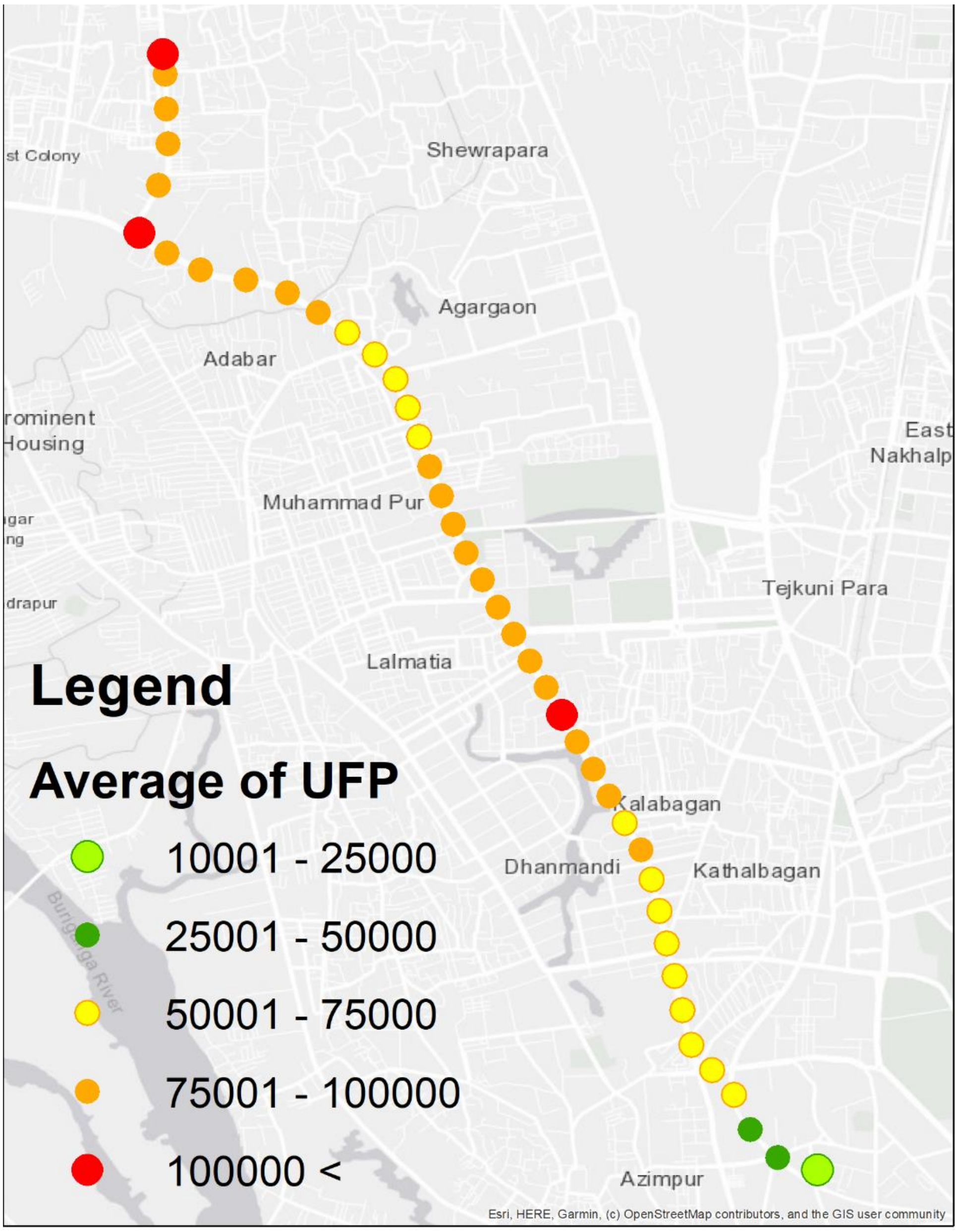

Figure C.3: Spatial variation of in-vehicle PNC measured in Private Car (Window Closed, Air Recirculation OFF) along the primary sampling route (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all sampling days.

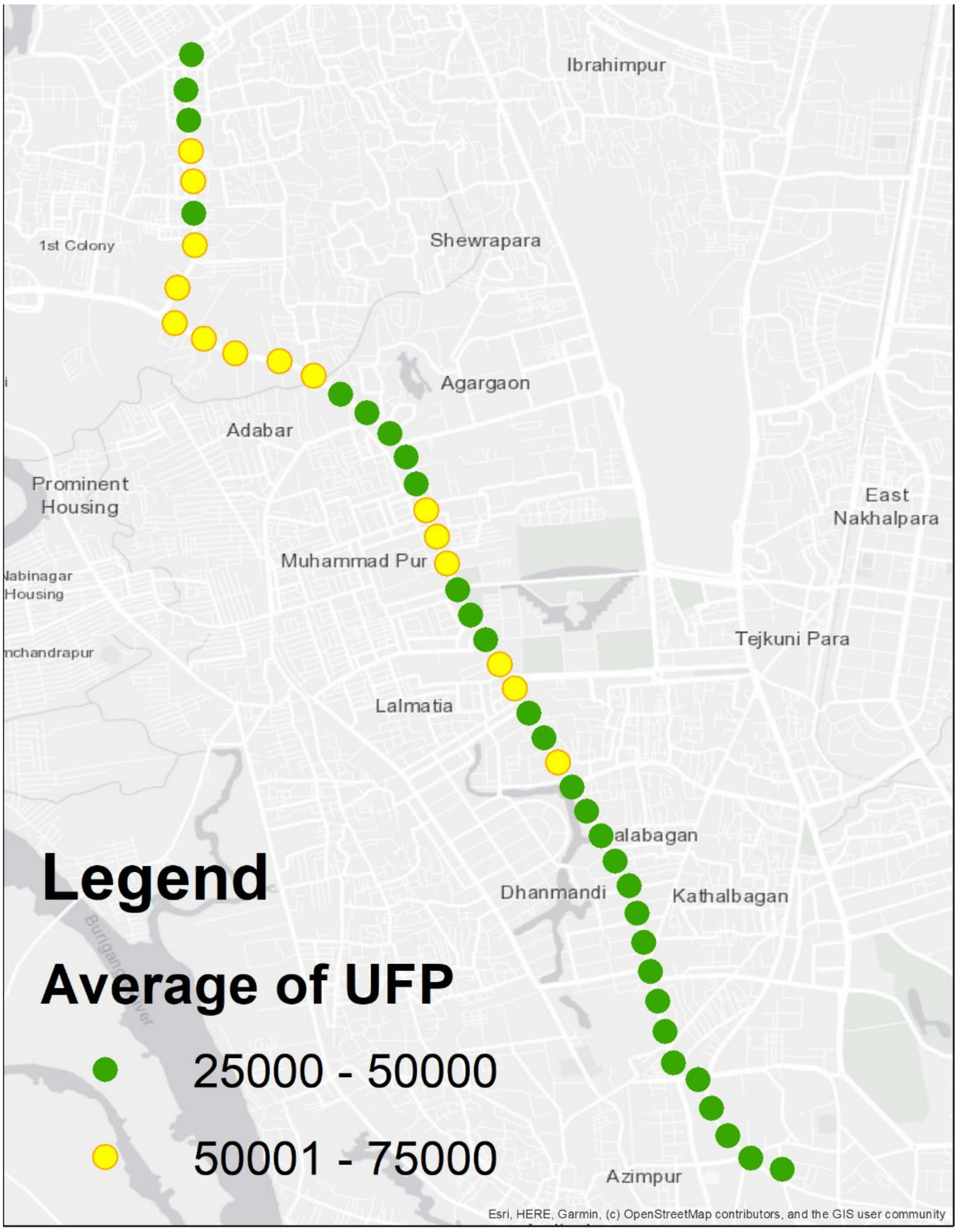

Figure C.4: Spatial variation of in-vehicle PNC measured in Private Car (Window Closed, Air Recirculation ON along the primary sampling route (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all sampling days.

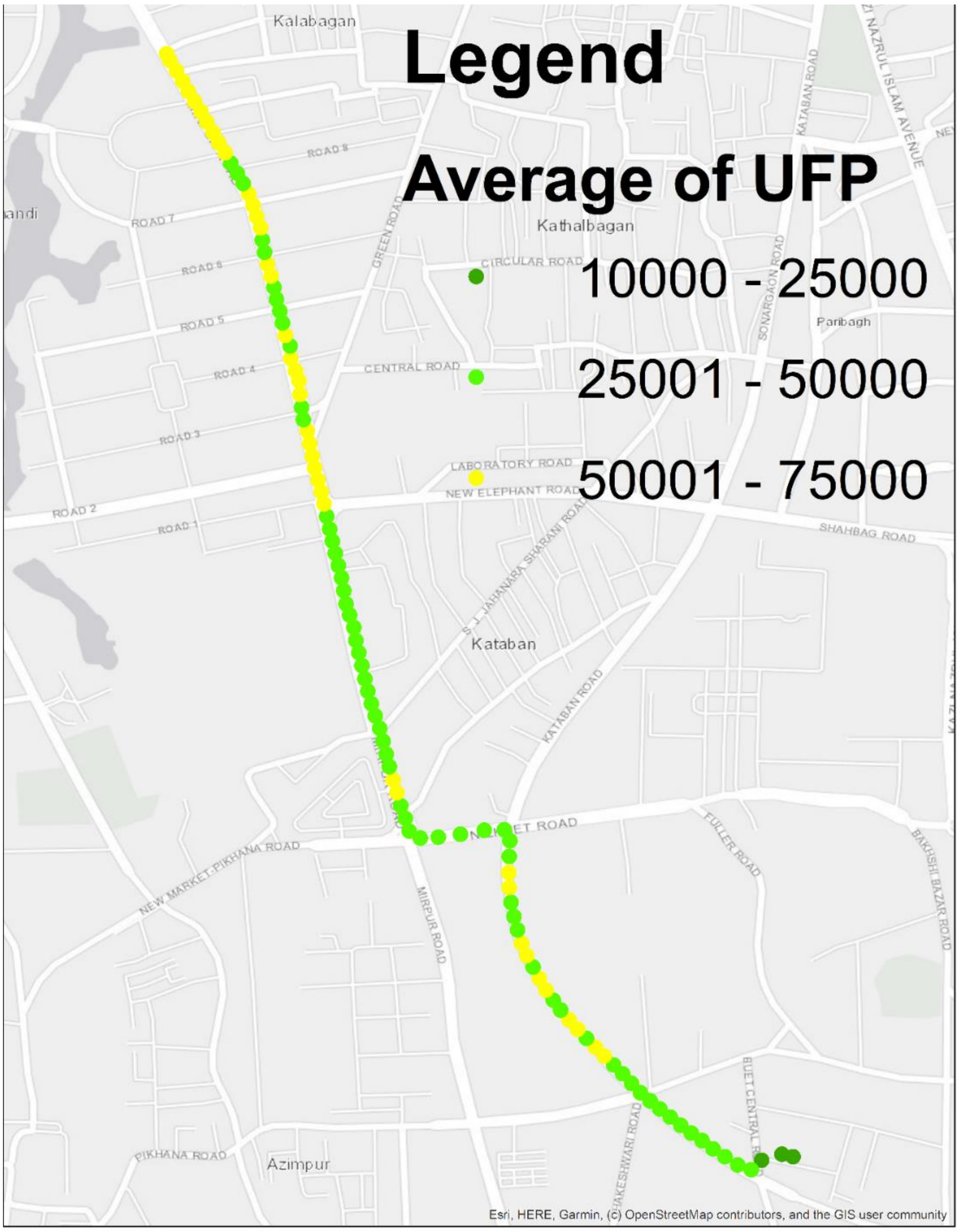

Figure C.5: Spatial variation of in-vehicle PNC measured in Rickshaw along subset of the primary sampling route (Azimpur to Dhanmondi). Concentrations are averaged over 25m road segment across all sampling days.

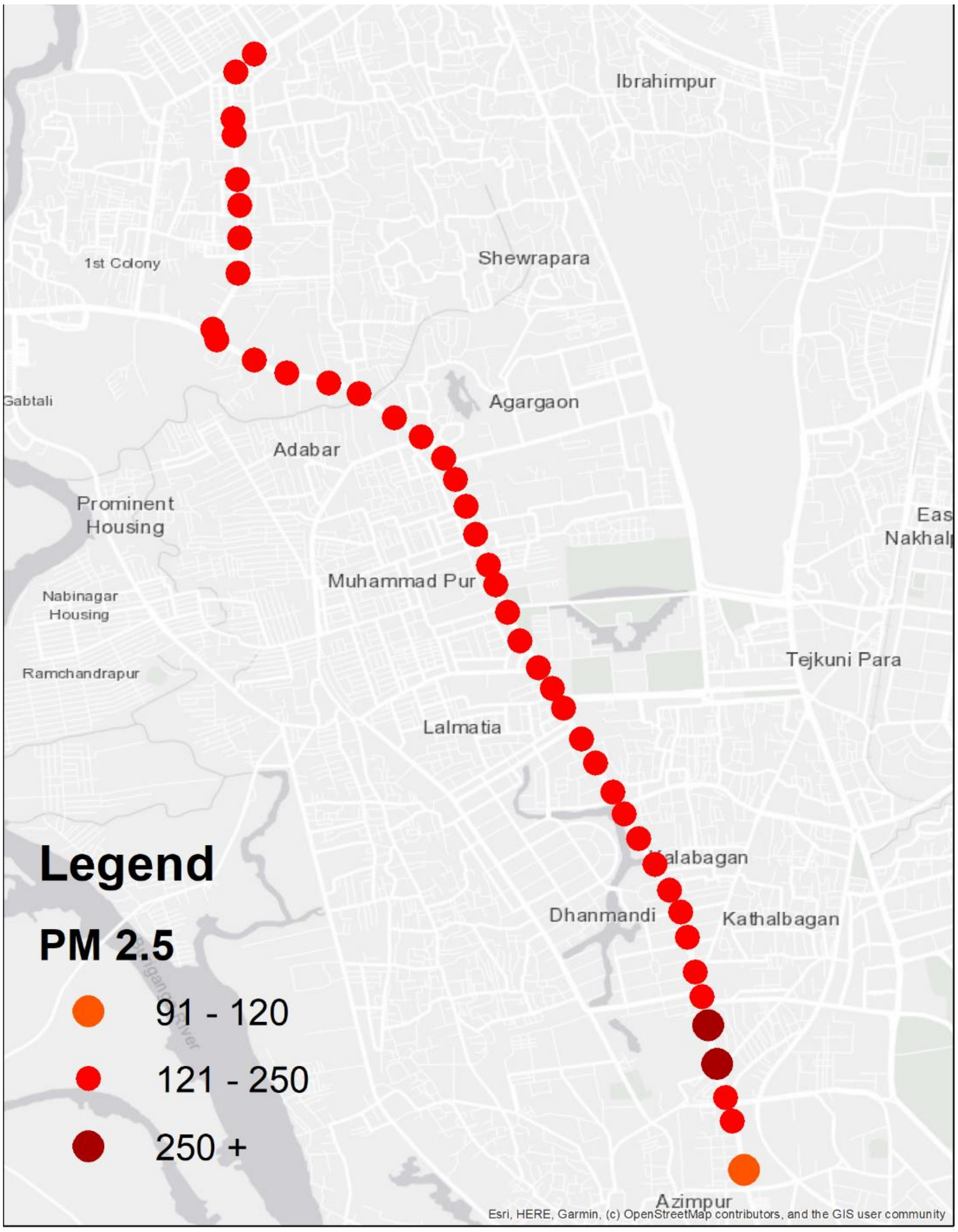

Figure C.6: Spatial variation of in-vehicle $PM_{2.5}$ concentrations measured in Bus mode along the primary sampling route (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all sampling days.

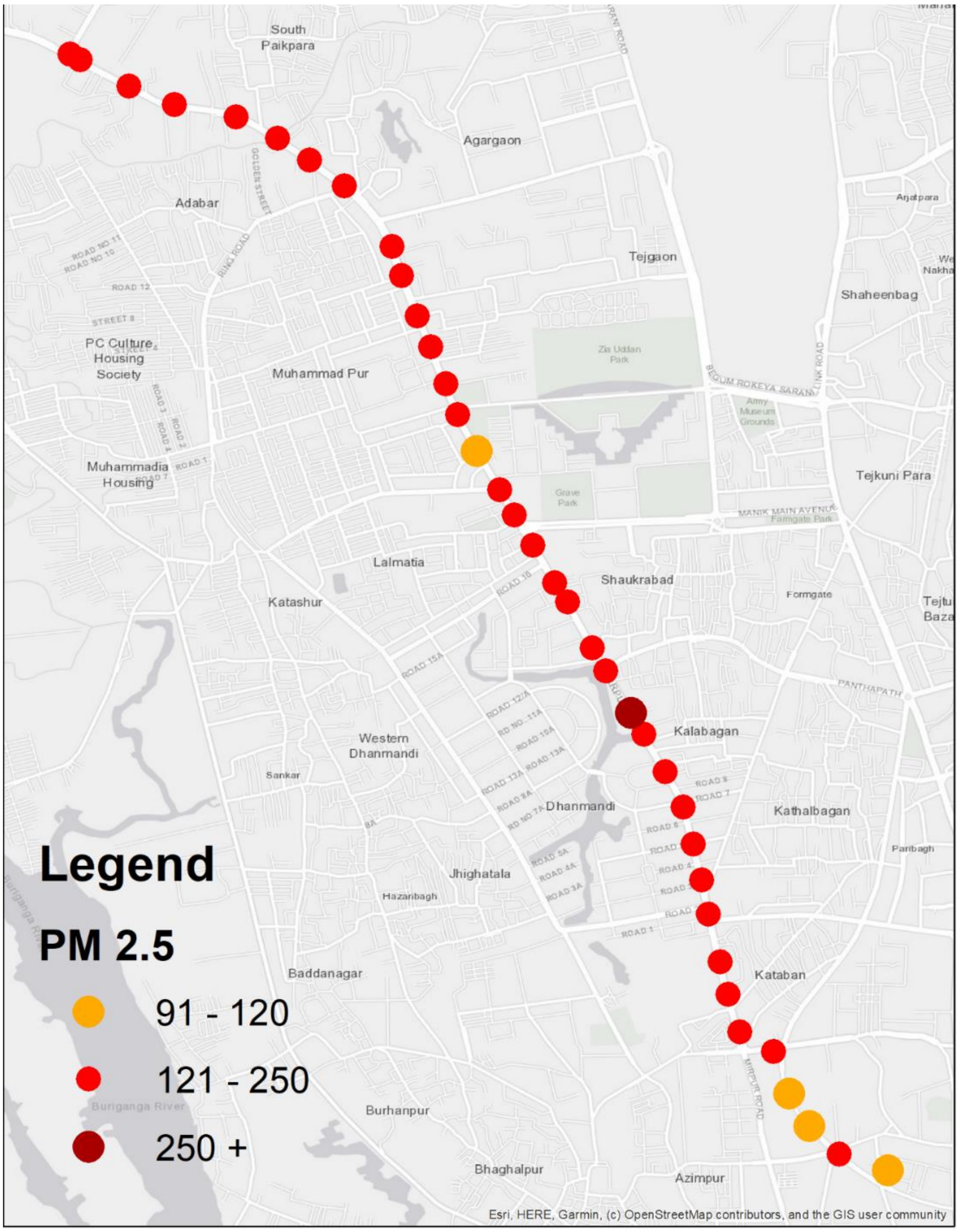

Figure C.7: Spatial variation of in-vehicle $PM_{2.5}$ concentrations measured in Private Car: Window Open along the primary sampling route (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all sampling days.

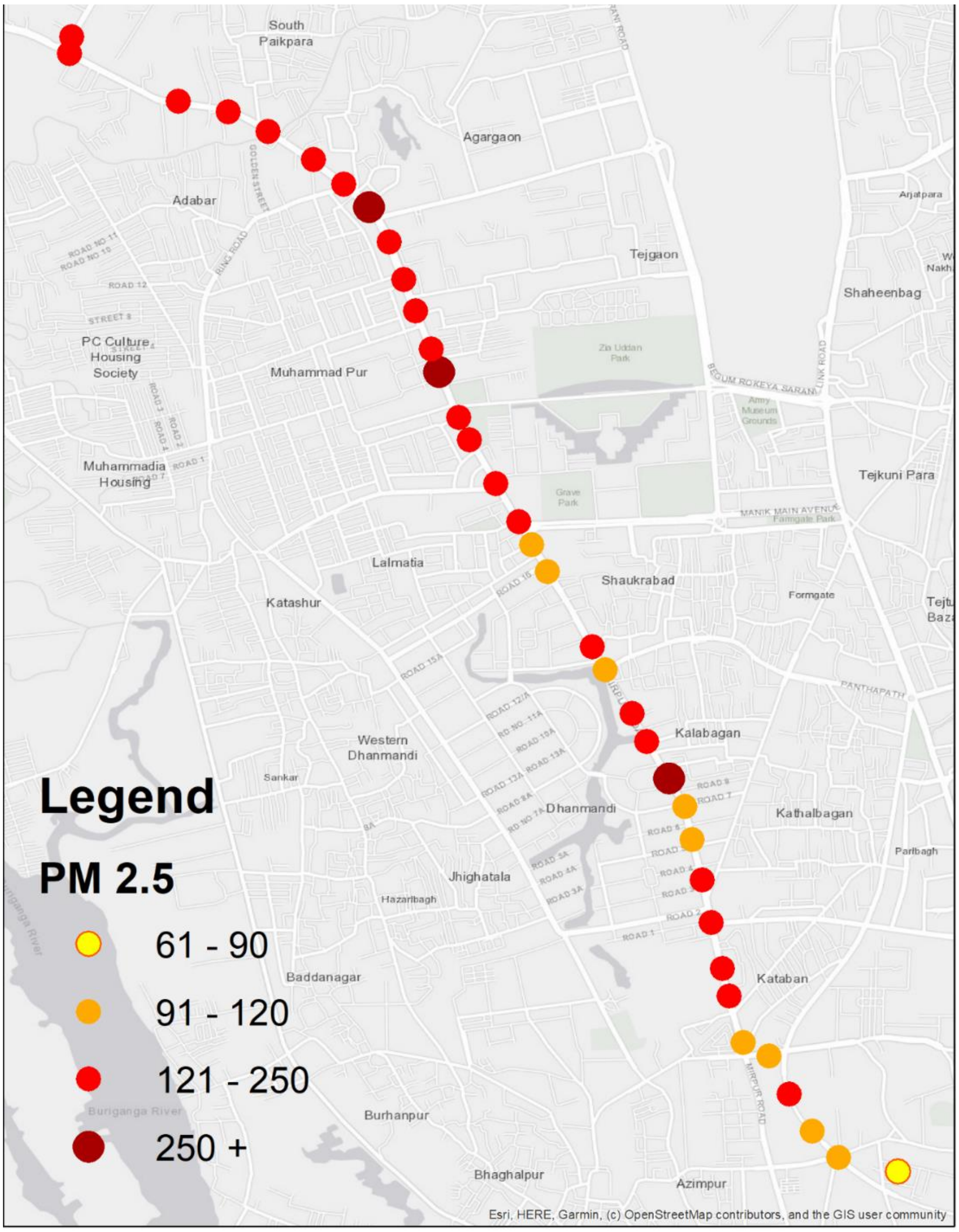

Figure C.8: Spatial variation of in-vehicle $PM_{2.5}$ concentrations measured in Private Car: Window Closed, Air Recirculation OFF mode along the primary sampling route (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all sampling days.

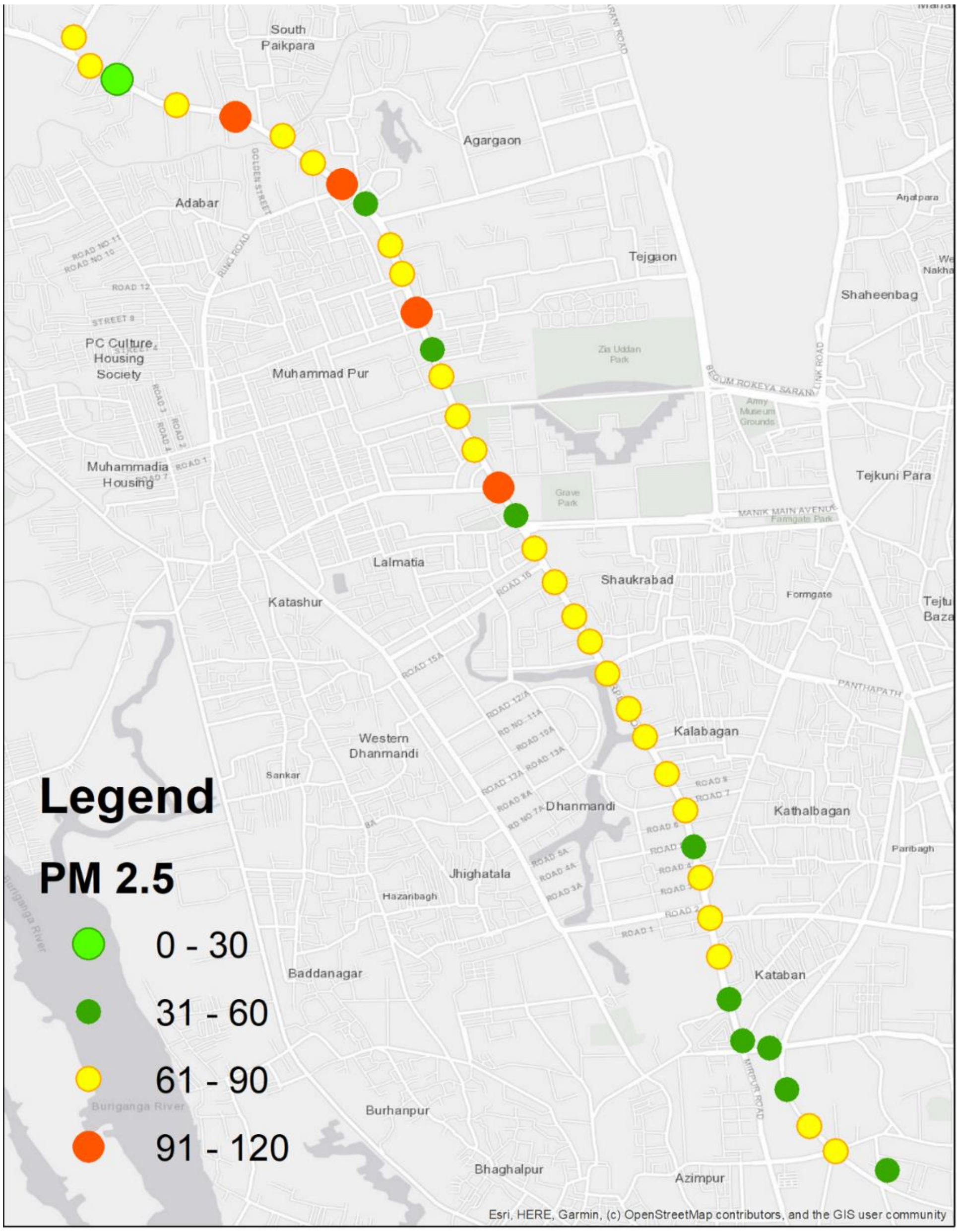

Figure C.9: Spatial variation of in-vehicle $PM_{2.5}$ concentrations measured in Private Car: Window Closed, Air Recirculation ON mode along the primary sampling route (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all sampling days.

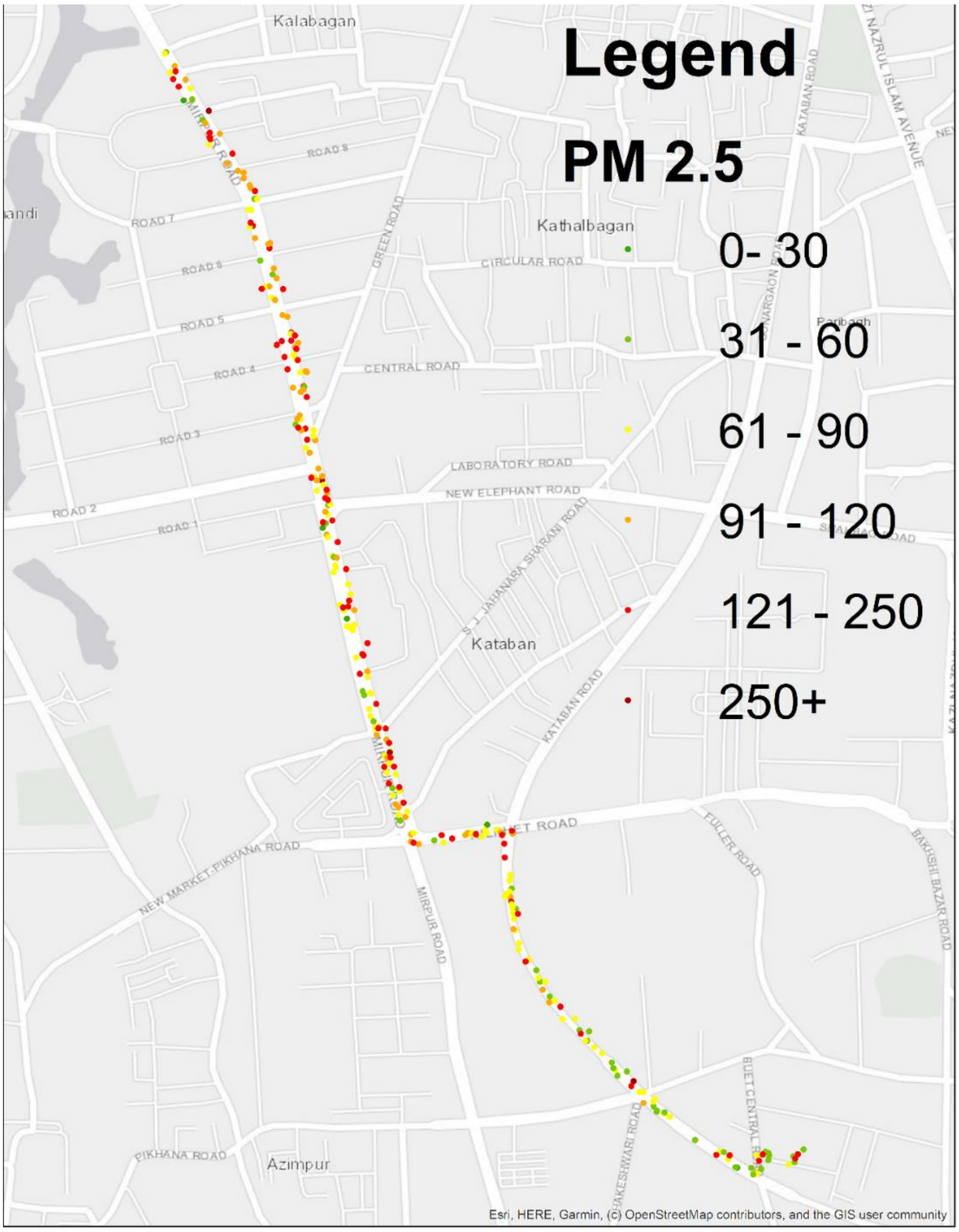

Figure C.10: Spatial variation of in-vehicle $PM_{2.5}$ concentrations measured in Rickshaw mode along the subset of primary sampling route (Azimpur to Dhanmondi). Concentrations are averaged over 25 m road segment across all sampling days.

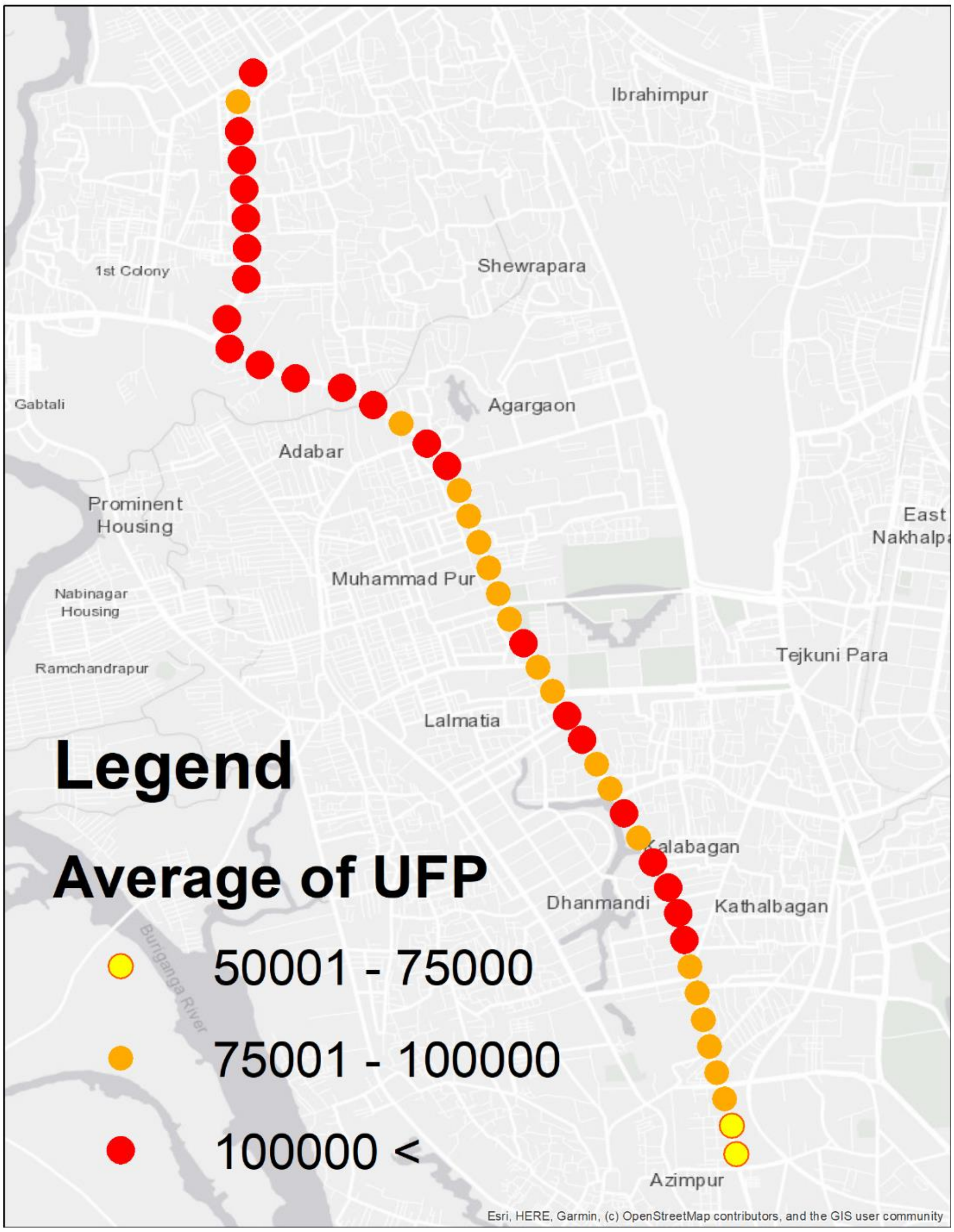

Figure C.11: Spatial variation of in-vehicle particle number concentrations measured in Bus mode along the primary sampling route in the morning (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all morning sampling days.

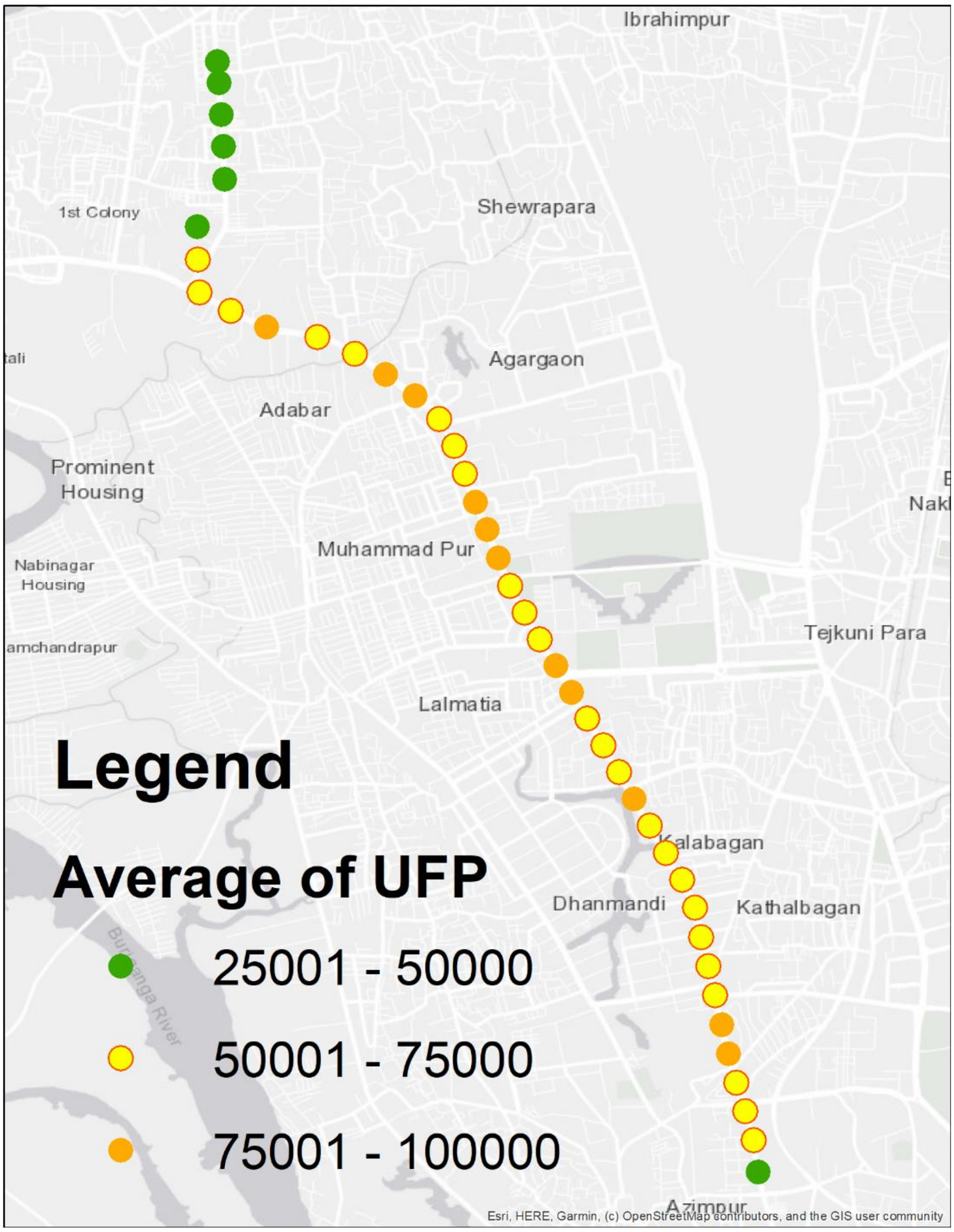

Figure C.12: Spatial variation of in-vehicle particle number concentrations measured in Bus mode along the primary sampling route in the midday (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all mid-day sampling days.

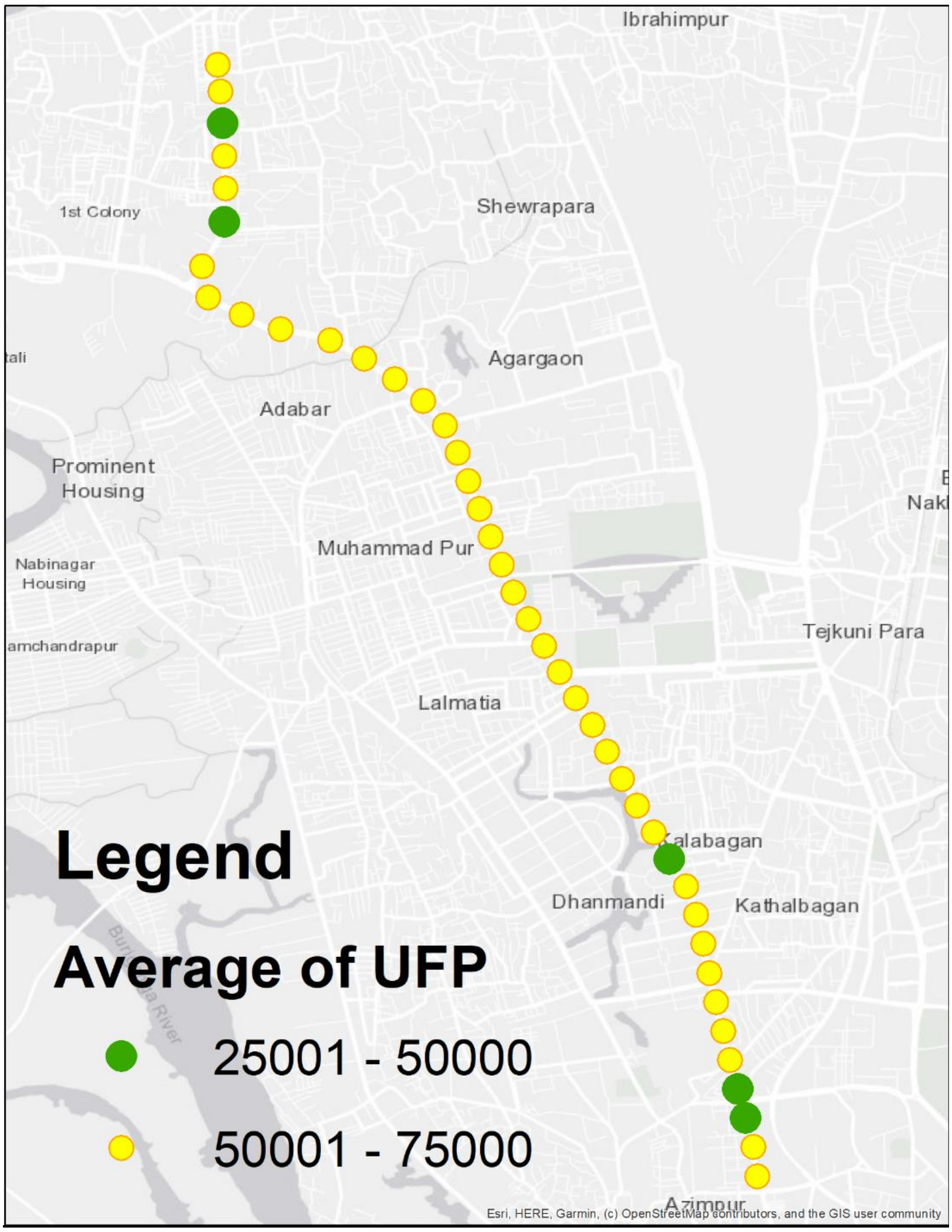

Figure C.13: Spatial variation of in-vehicle particle number concentrations measured in Bus mode along the primary sampling route in the afternoon (Azimpur to Mirpur-1). Concentrations are averaged over 200 m road segment across all afternoon sampling days.

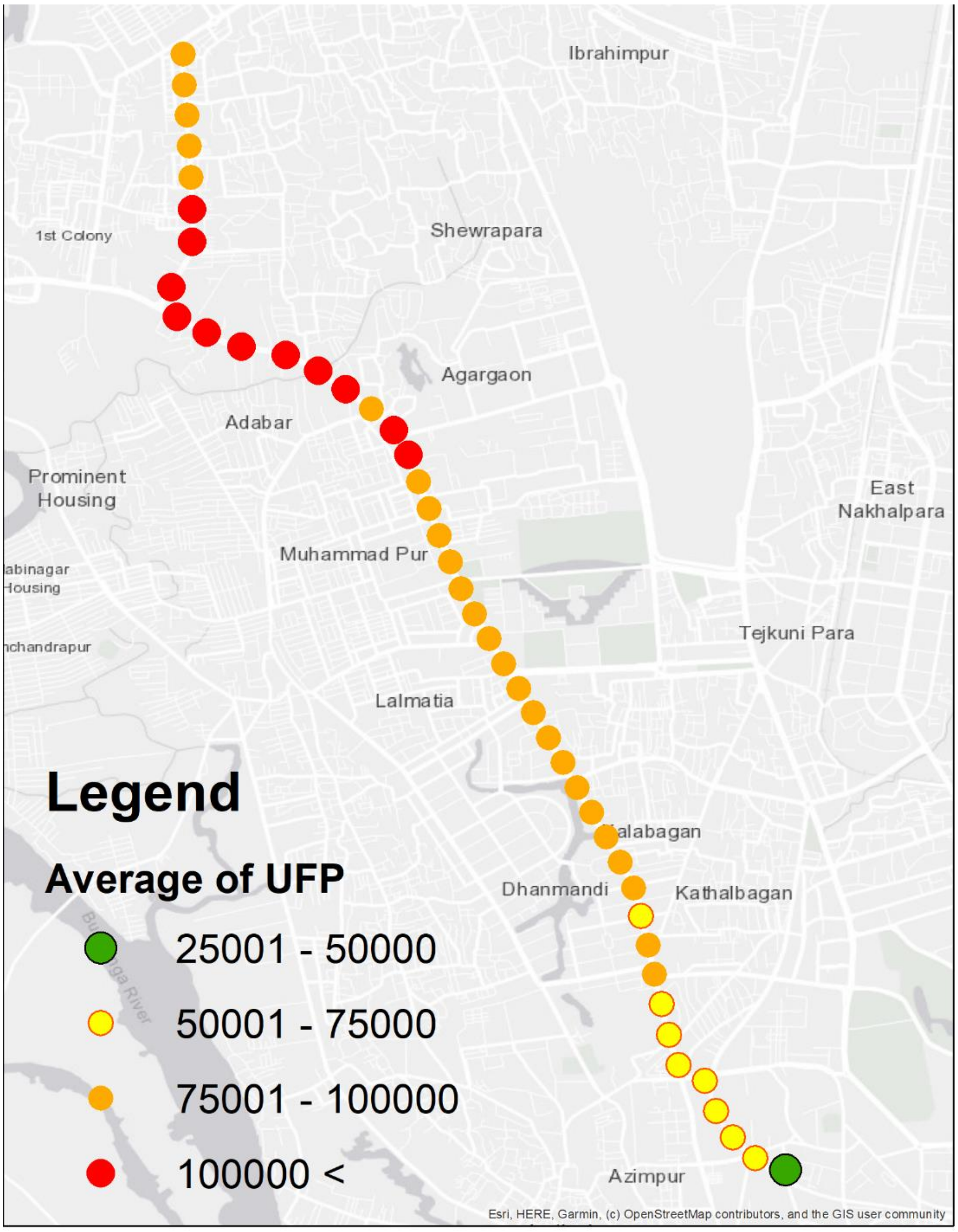

Figure C.14: Spatial variation of in-vehicle particle number concentrations measured in Private Car (Window Open) mode along the primary sampling route in the morning. Concentrations are averaged over 200 m road segment across all morning sampling days.

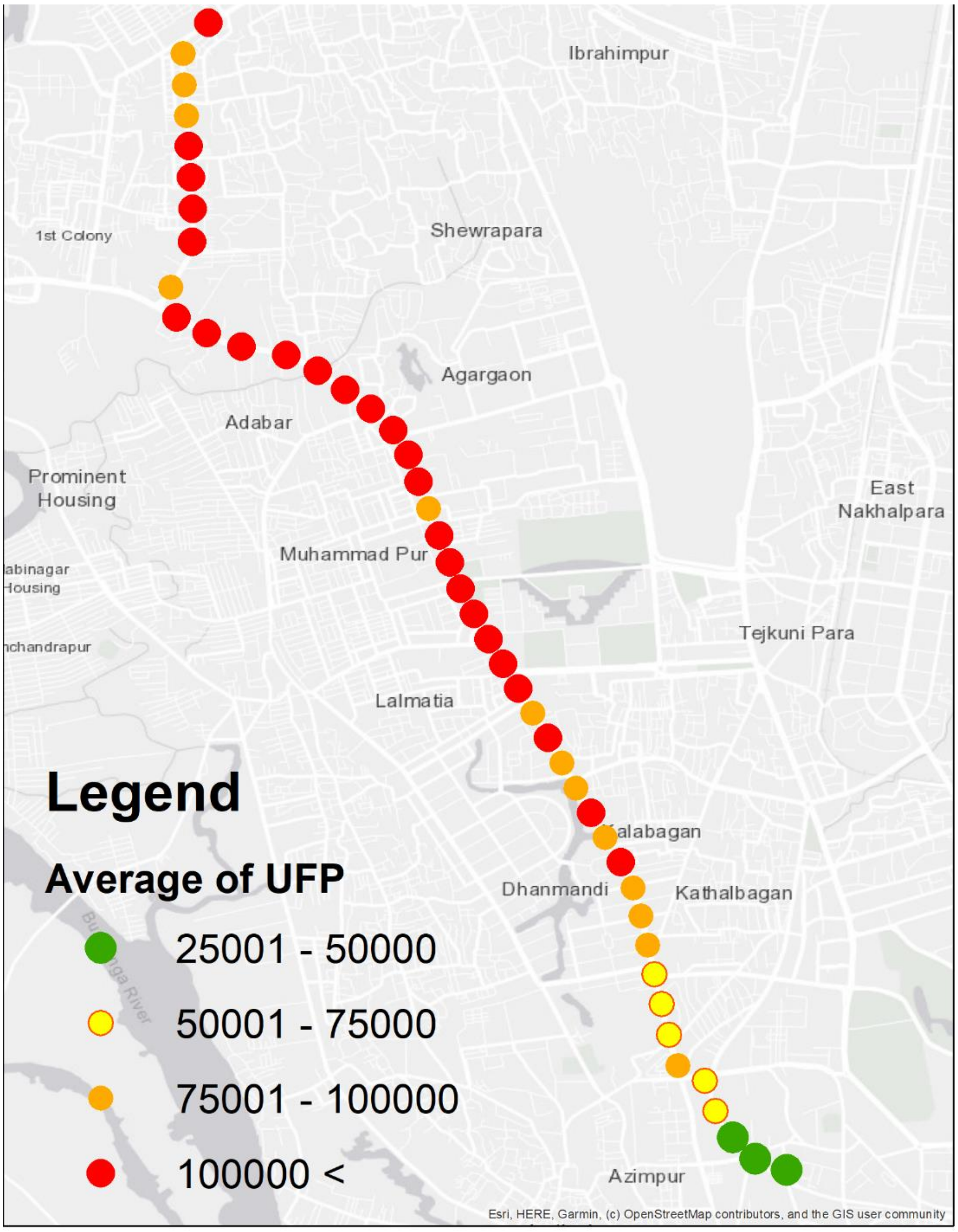

Figure C.15: Spatial variation of in-vehicle particle number concentrations measured in Private Car (Window Open) mode along the primary sampling route in mid-day. Concentrations are averaged over 200 m road segment across all mid-day sampling days.

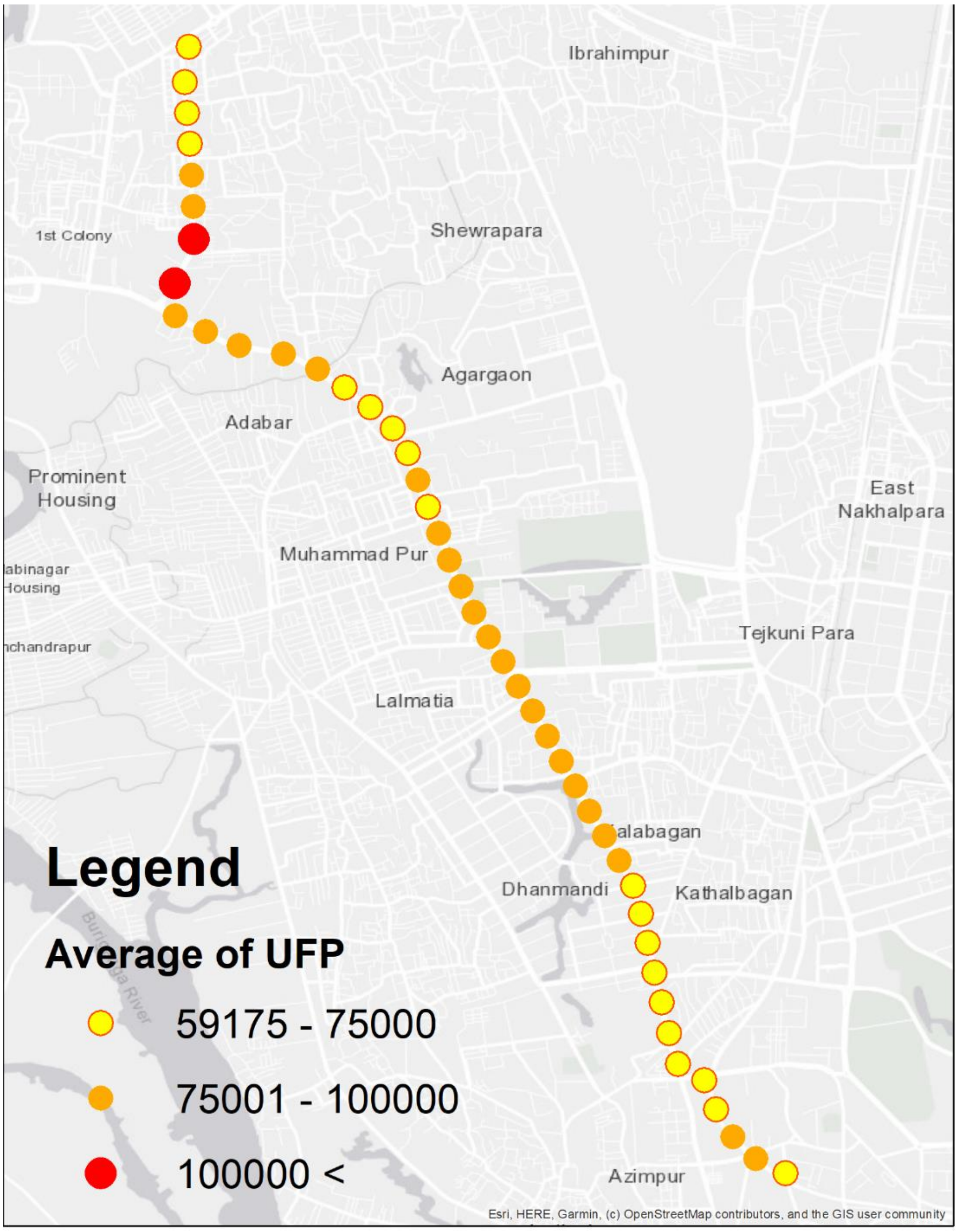

Figure C.16: Spatial variation of in-vehicle particle number concentrations measured in Private Car (Window Open) mode along the primary sampling route in the afternoon. Concentrations are averaged over 200 m road segment across all afternoon sampling days.

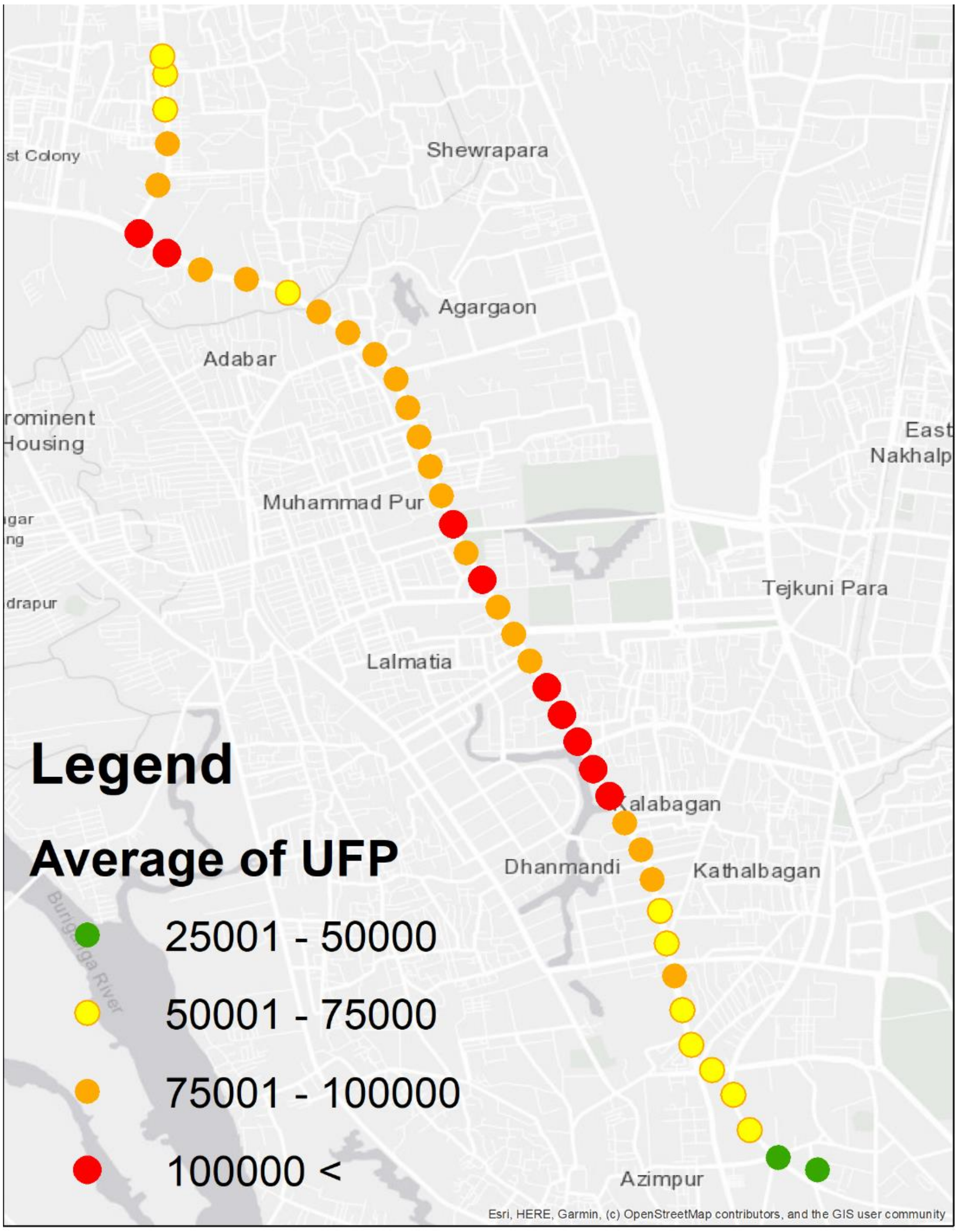

Figure C.17: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation OFF mode along the primary sampling route in the Morning. Concentrations are averaged over 200 m road segment across all morning sampling days.

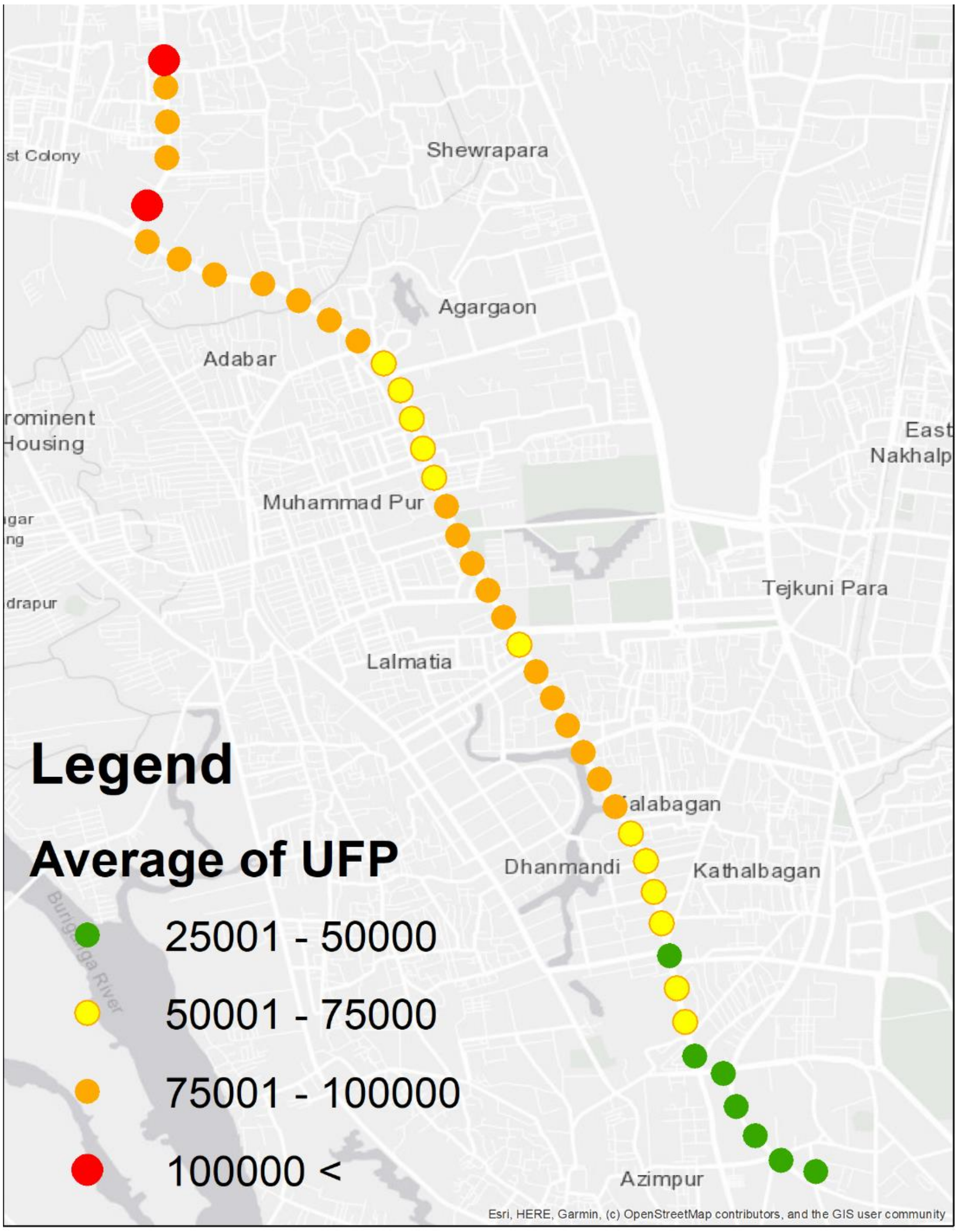

Figure C.18: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation OFF mode along the primary sampling route in mid-day. Concentrations are averaged over 200 m road segment across all mid-day sampling days.

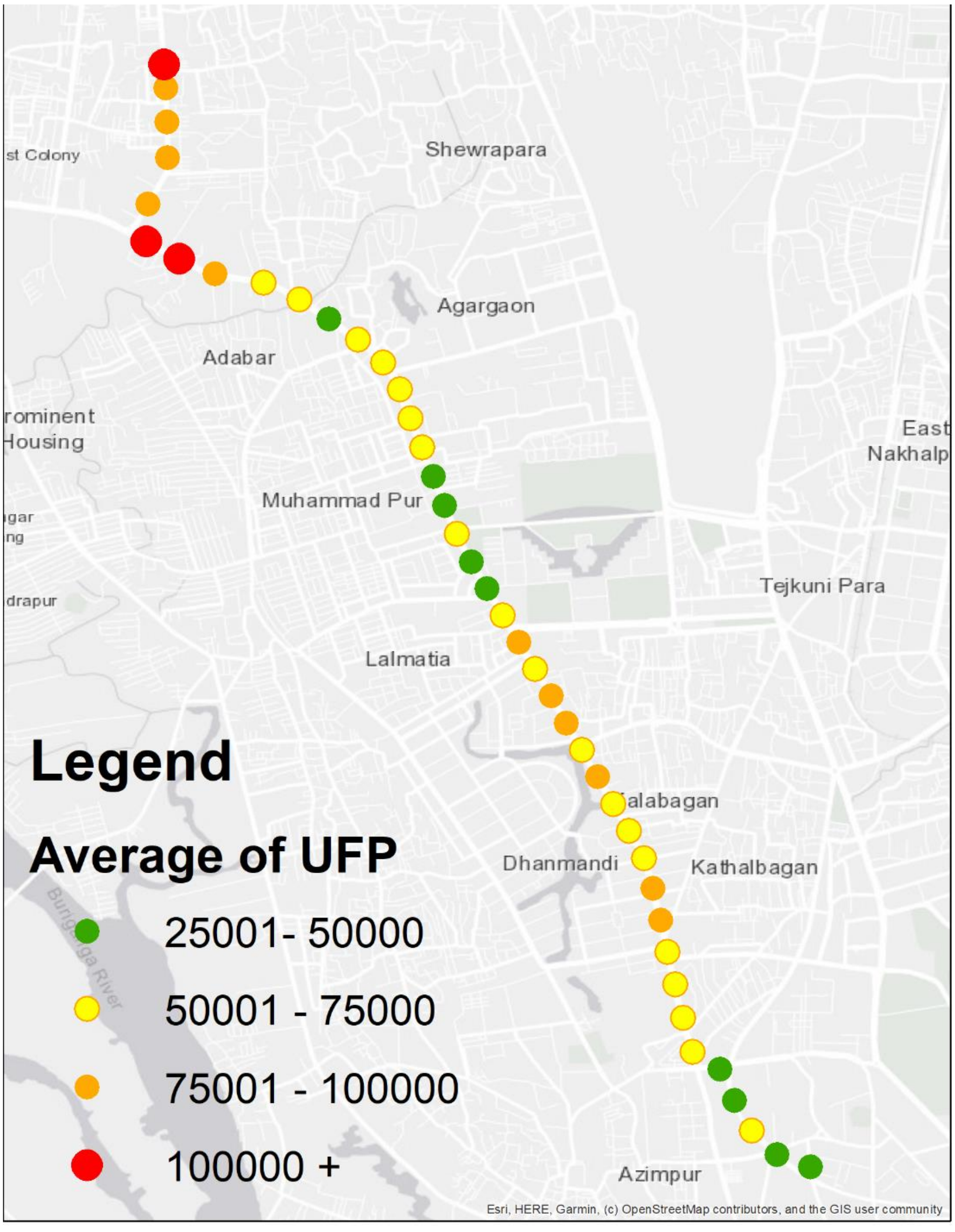

Figure C.19: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation OFF mode along the primary sampling route in the afternoon. Concentrations are averaged over 200 m road segment across all afternoon sampling days.

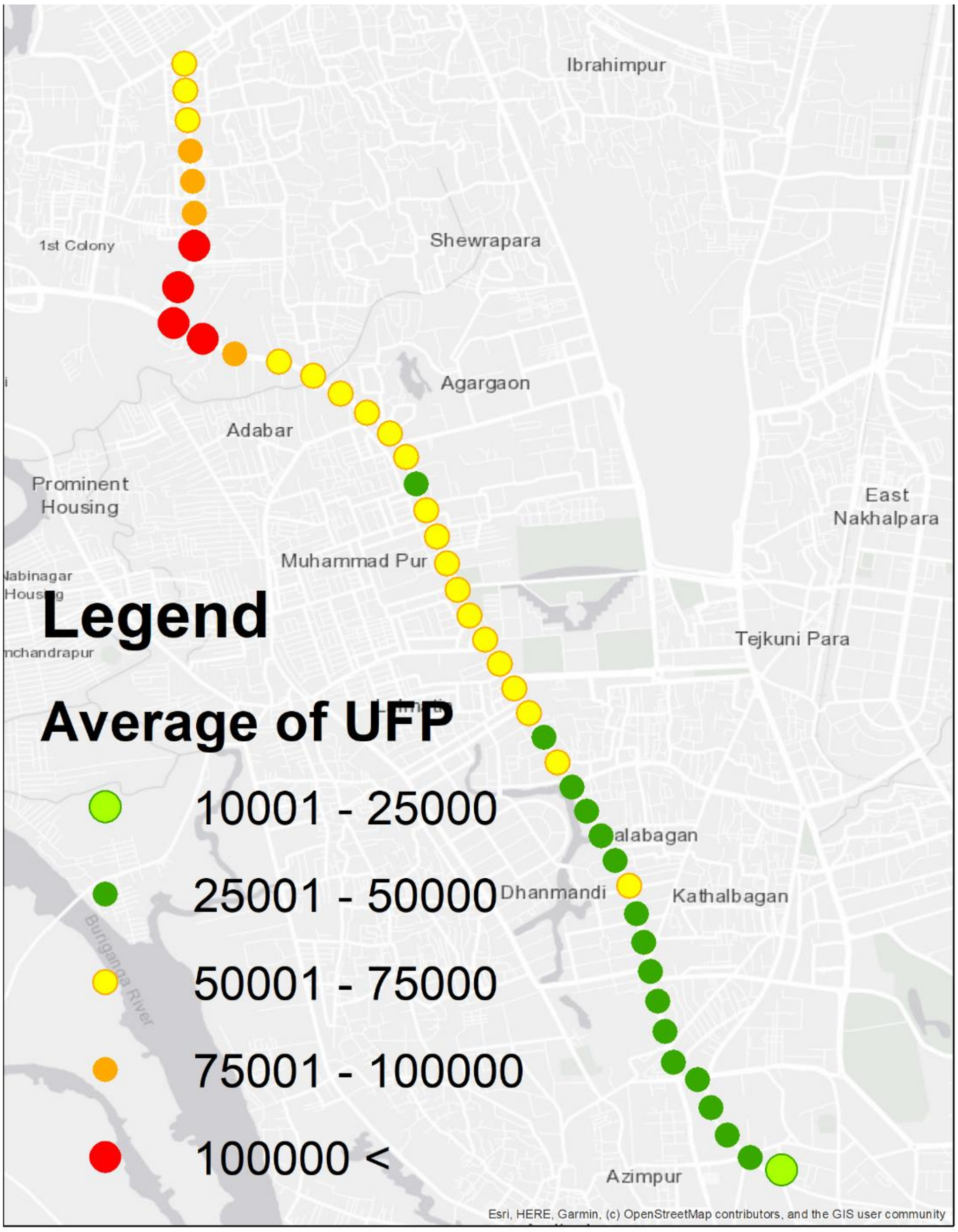

Figure C.20: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation ON mode along the primary sampling route in the morning. Concentrations are averaged over 200 m road segment across all morning sampling days.

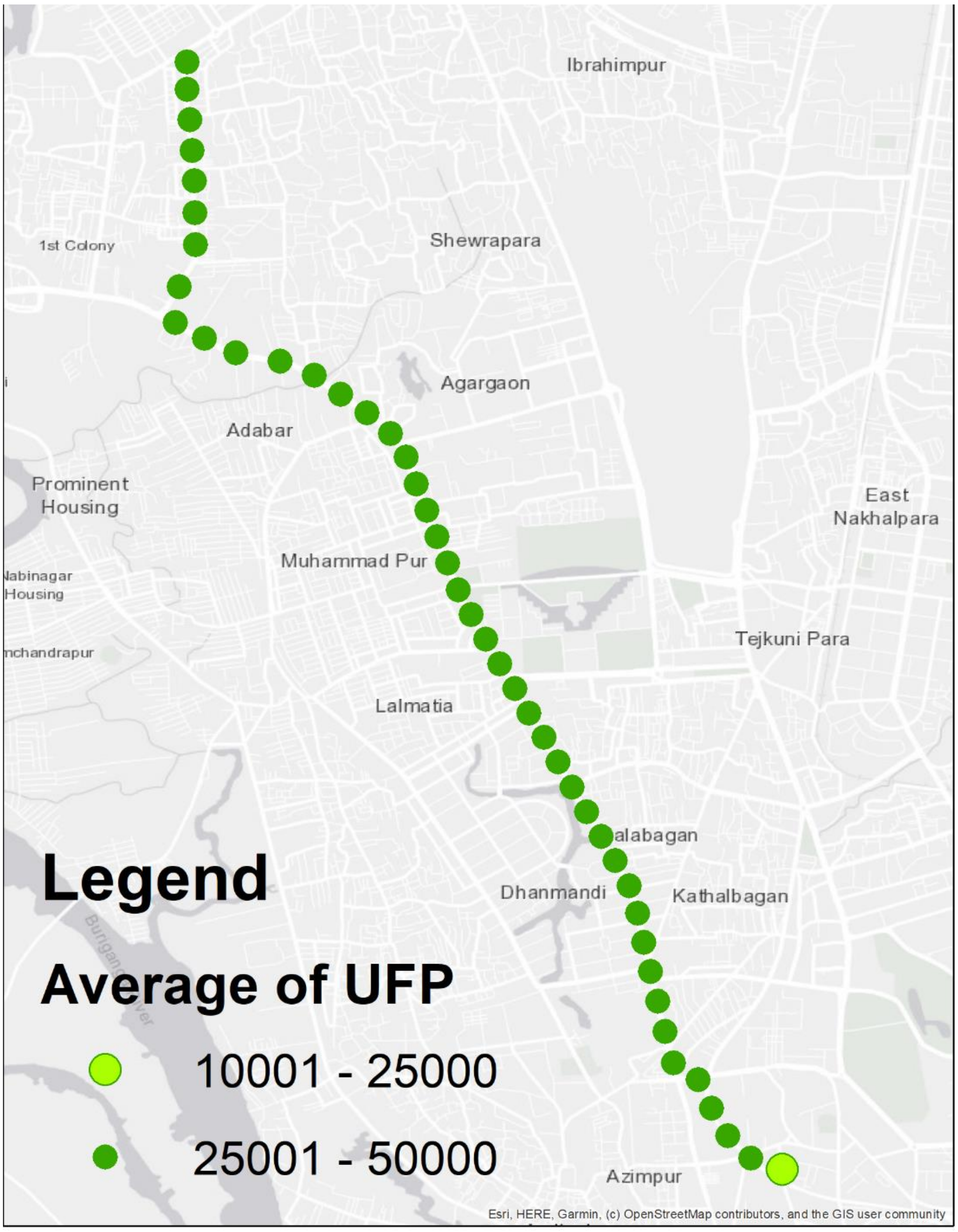

Figure C.21: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation ON mode along the primary sampling route in midday. Concentrations are averaged over 200 m road segment across all mid-day sampling days.

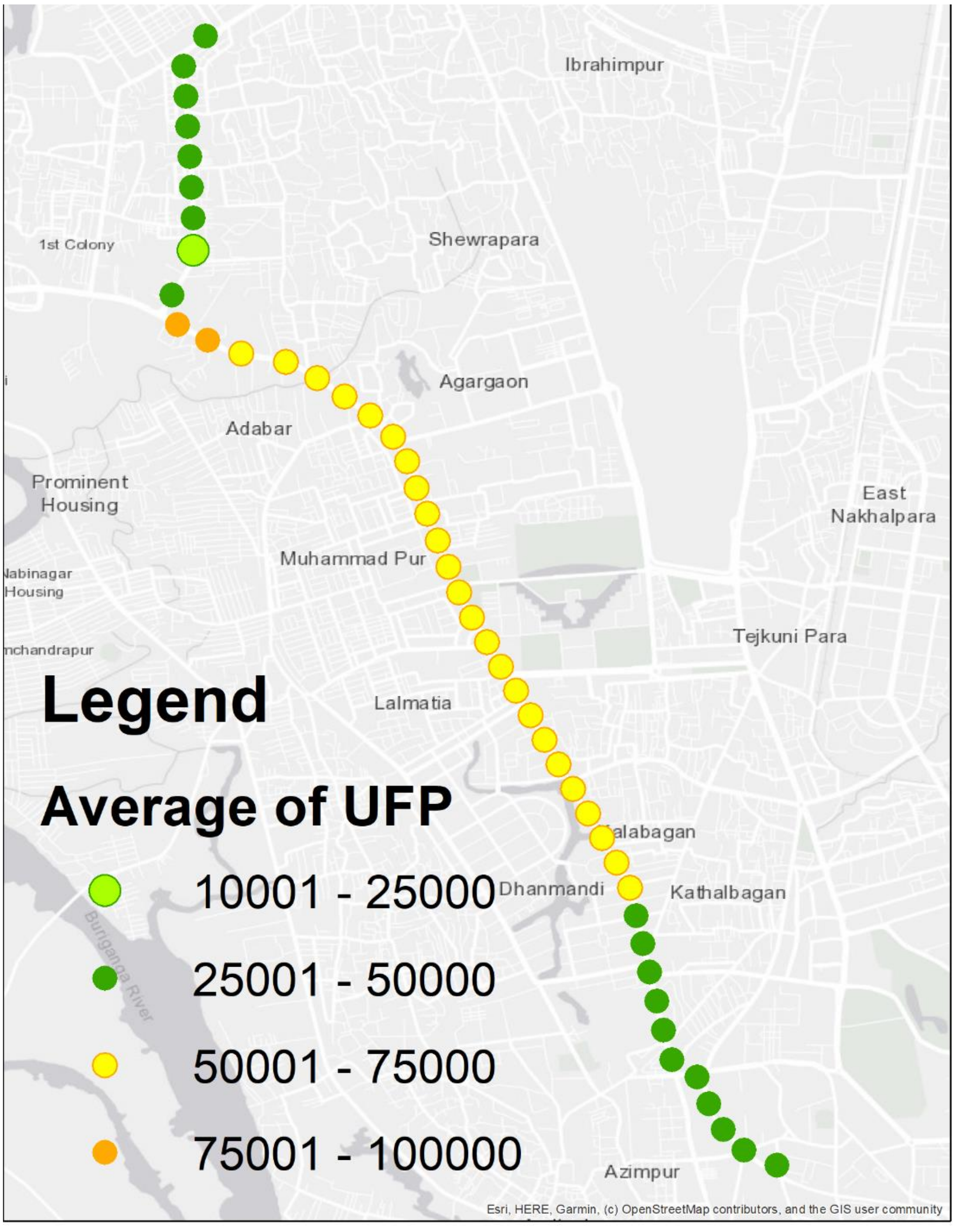

Figure C.22: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation ON mode along the primary sampling route in the afternoon. Concentrations are averaged over 200 m road segments across all afternoon sampling days.

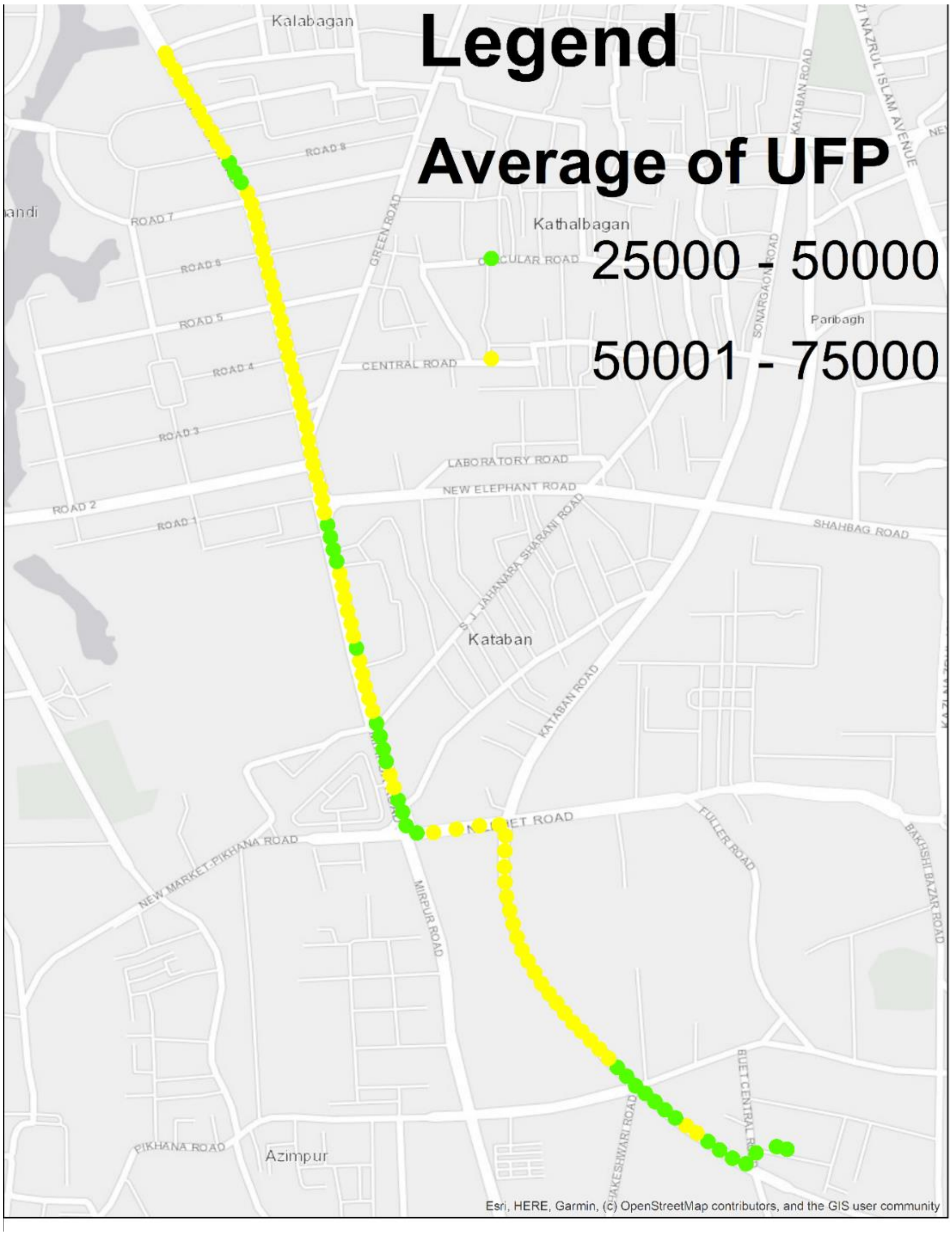

Figure C.23: Spatial variation of in-vehicle particle number concentrations measured in Rickshaw mode along the primary sampling route in the Midday (Azimpur to Dhanmondi). Concentrations are averaged over 25 m road segments across all mid-day sampling days.

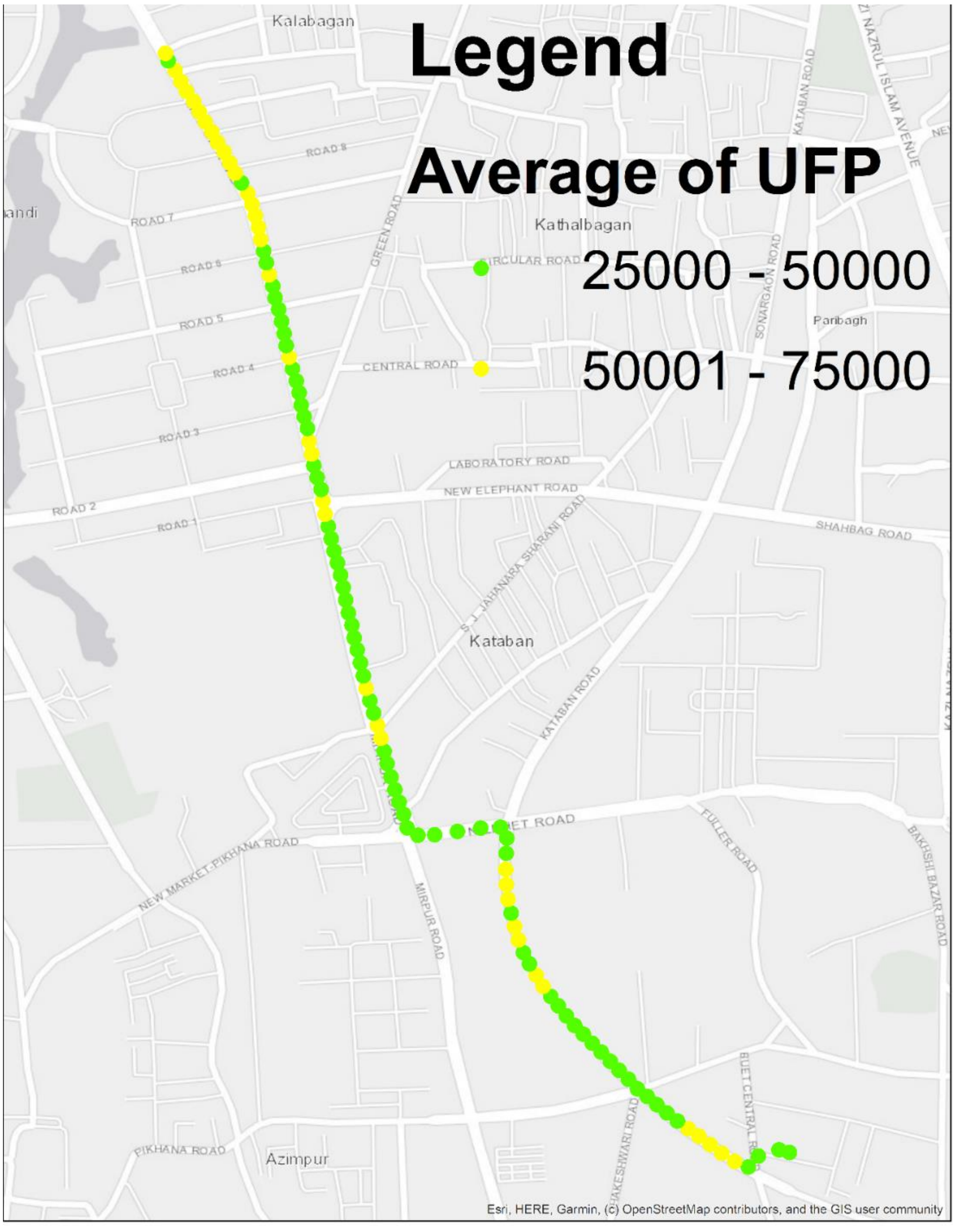

Figure C.24: Spatial variation of in-vehicle particle number concentrations measured in Rickshaw mode on the primary sampling route in the afternoon (Azimpur to Dhanmondi). Concentrations are averaged over 25 m road segments across all afternoon sampling days.

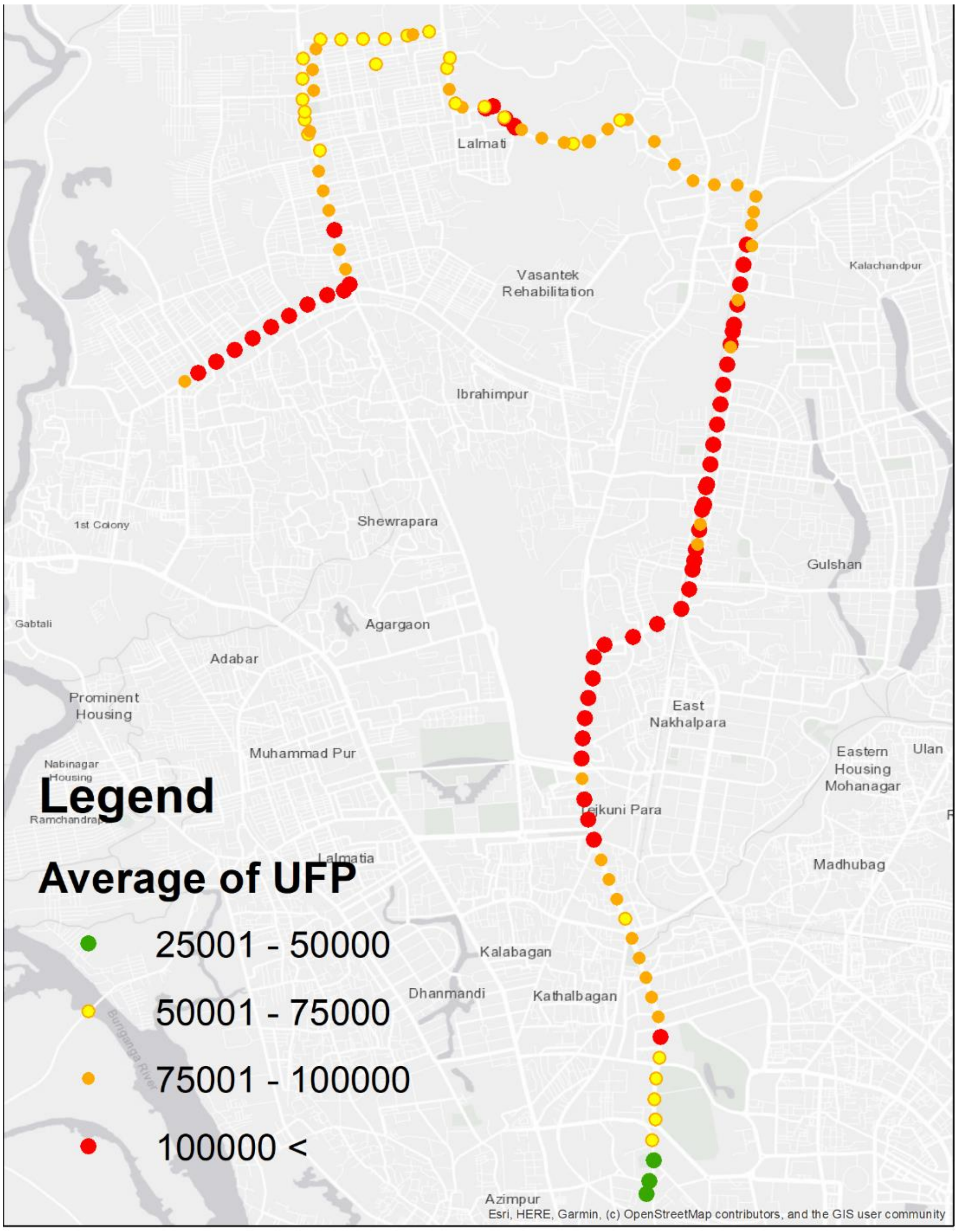

Figure C.25: Spatial variation of in-vehicle particle number concentrations measured in Private Car (Window Open) mode along the additional sampling route. Concentrations are averaged over 200 m road segments across all sampling days.

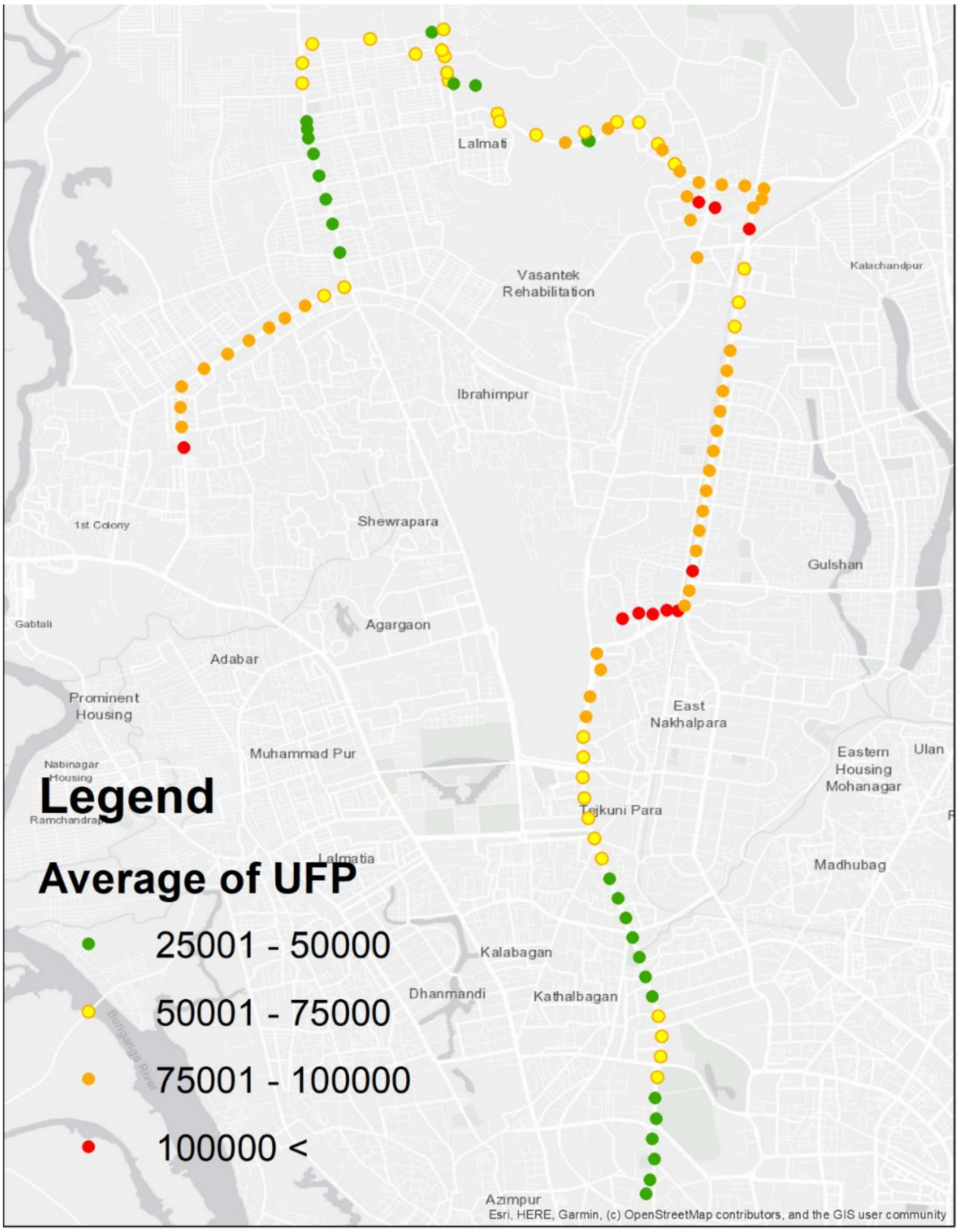

Figure C.26: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation OFF) mode along the additional sampling route. Concentrations are averaged over 200 m road segments across all sampling days.

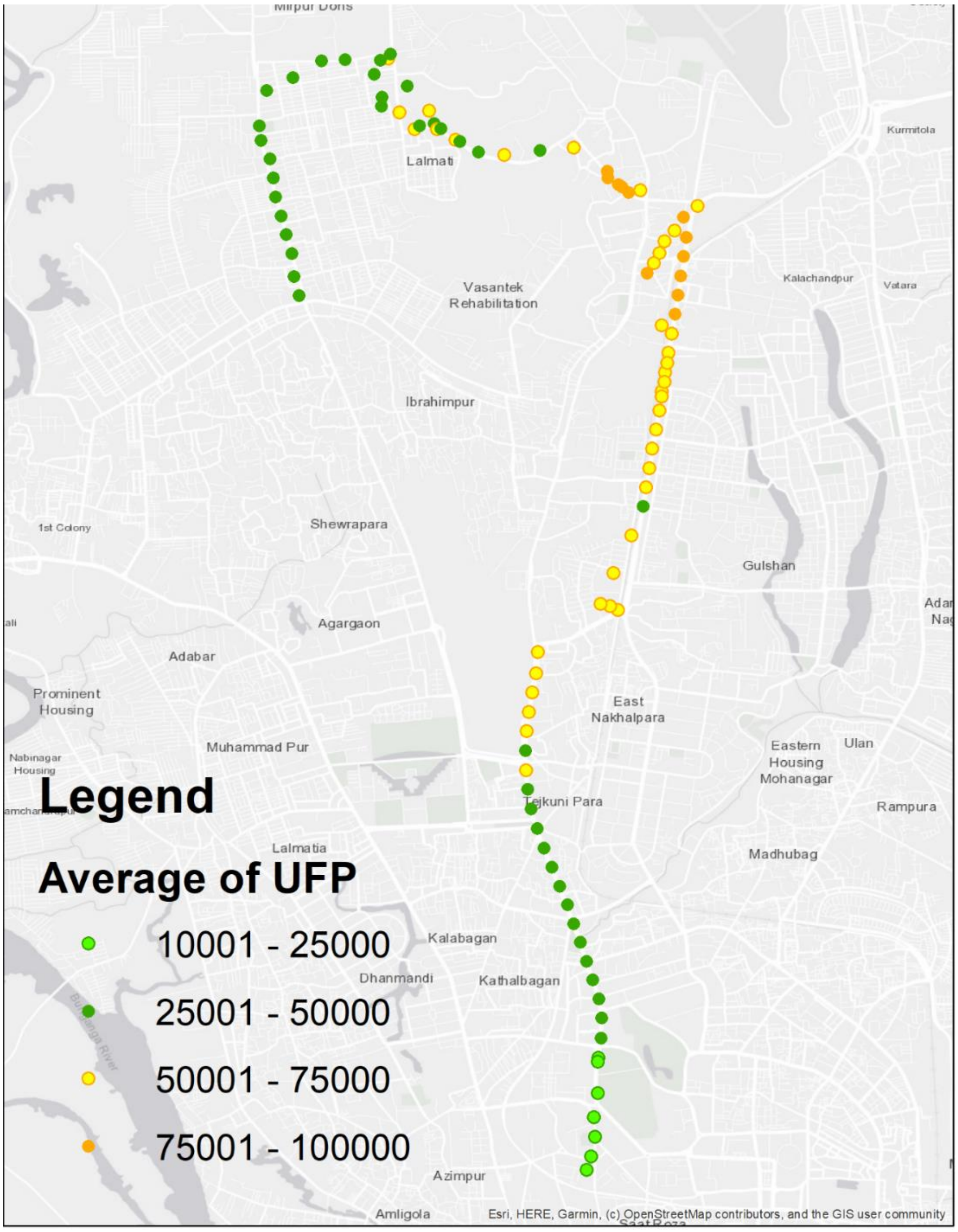

Figure C27: Spatial variation of in-vehicle particle number concentrations measured Private Car: Window Closed, Air Recirculation ON mode along the additional sampling route. Concentrations are averaged over 200 m road segments across all sampling days.

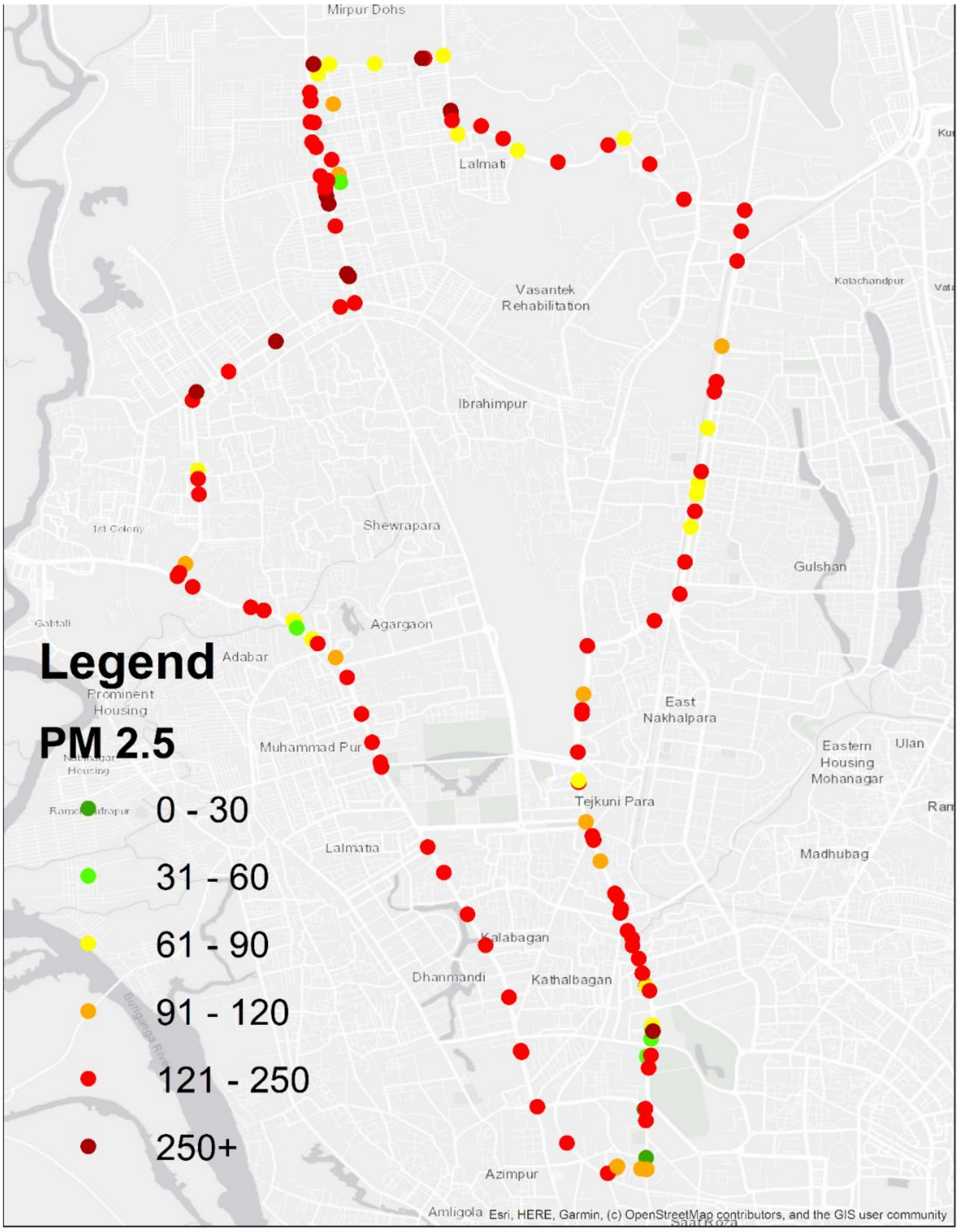

Figure C.28: Spatial variation of in-vehicle $PM_{2.5}$ concentrations measured in Private Car (Window Open) mode along the primary and additional sampling routes. Concentrations are averaged over 200 m road segments across all sampling days.

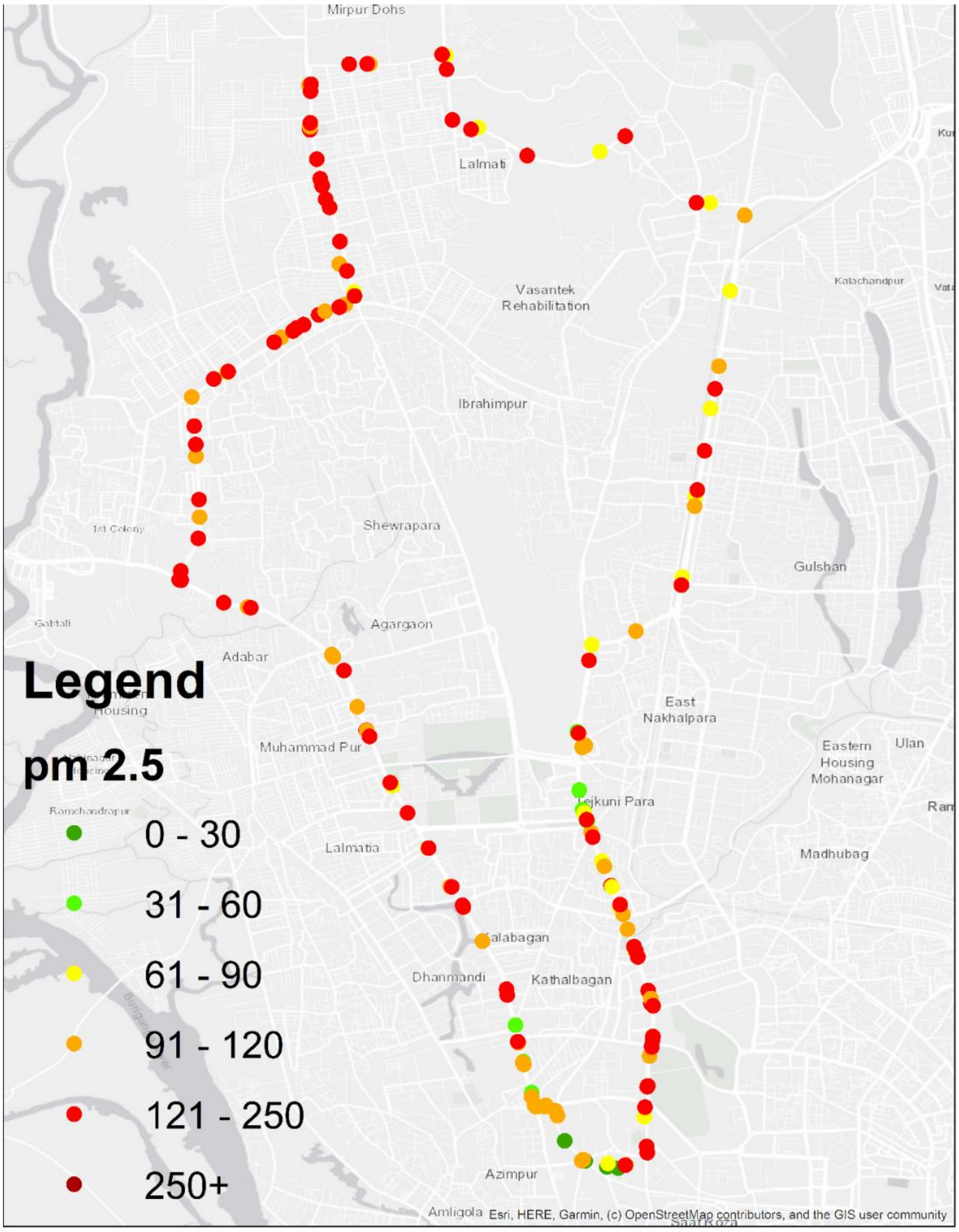

Figure C.29: Spatial variation of in-vehicle $PM_{2.5}$ concentrations measured in Private Car: Window Closed, Air Recirculation OFF mode along the primary and additional sampling routes. Concentrations are averaged over 200 m road segments across all sampling days.

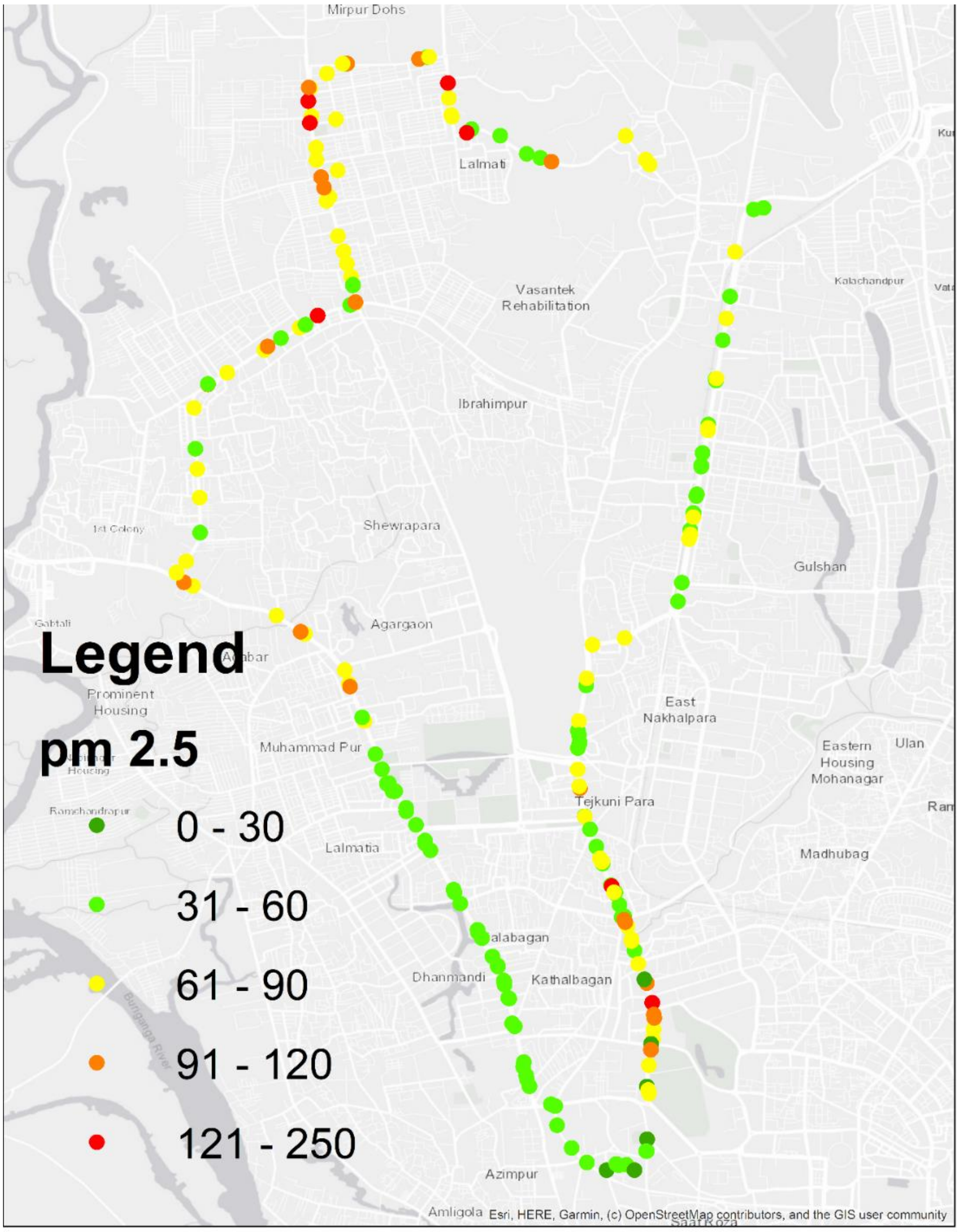

Figure C.30: Spatial variation of in-vehicle $PM_{2.5}$ concentrations measured in Private Car: Window Closed, Air Recirculation ON mode along the primary and additional sampling route. Concentrations are averaged over 200 m road segments across all sampling days.

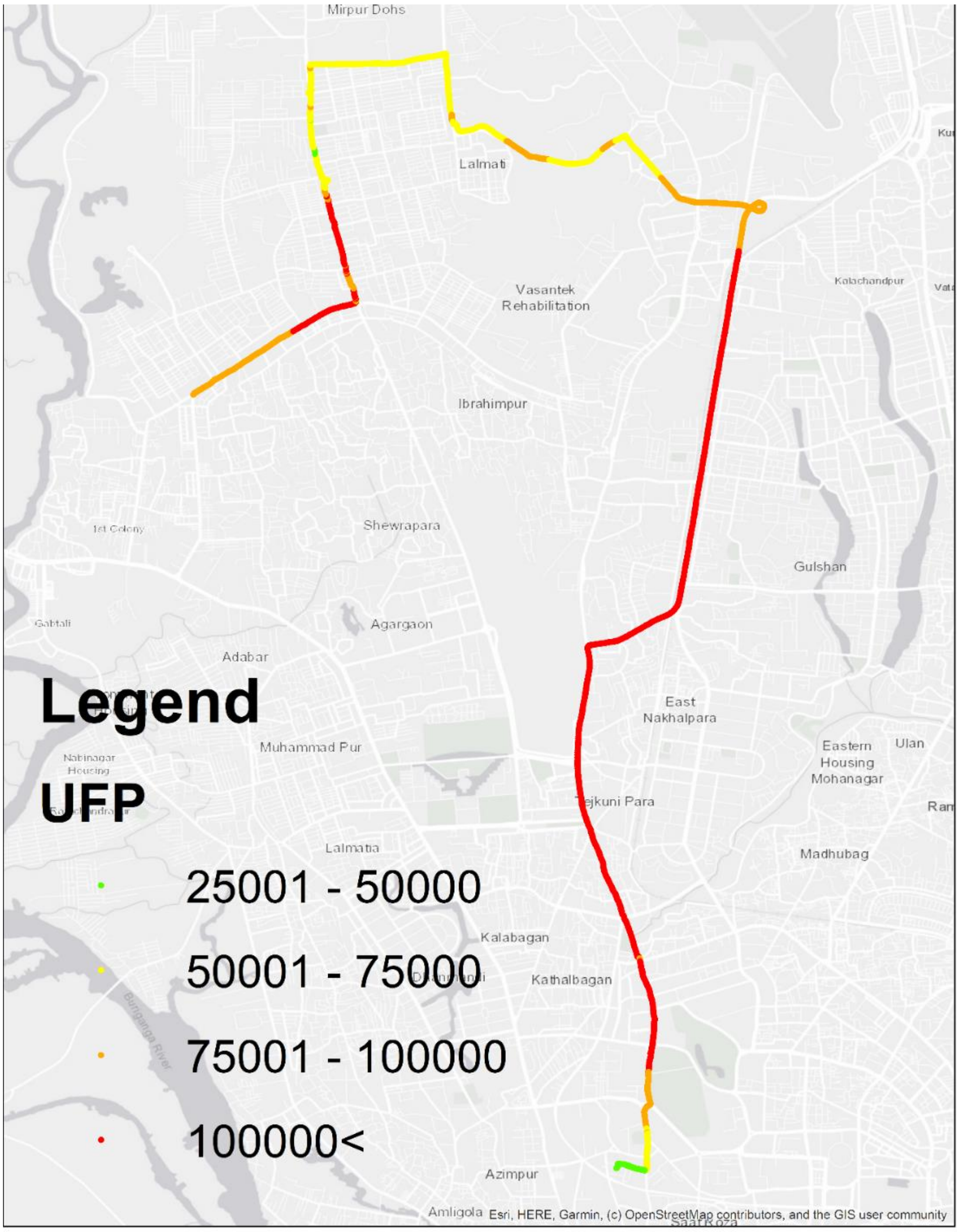

Figure C.31: Spatial variation of in-vehicle particle number concentrations measured in Private Car (Window Open) mode along the additional sampling route in the morning. Concentrations are averaged over 25 m road segments.

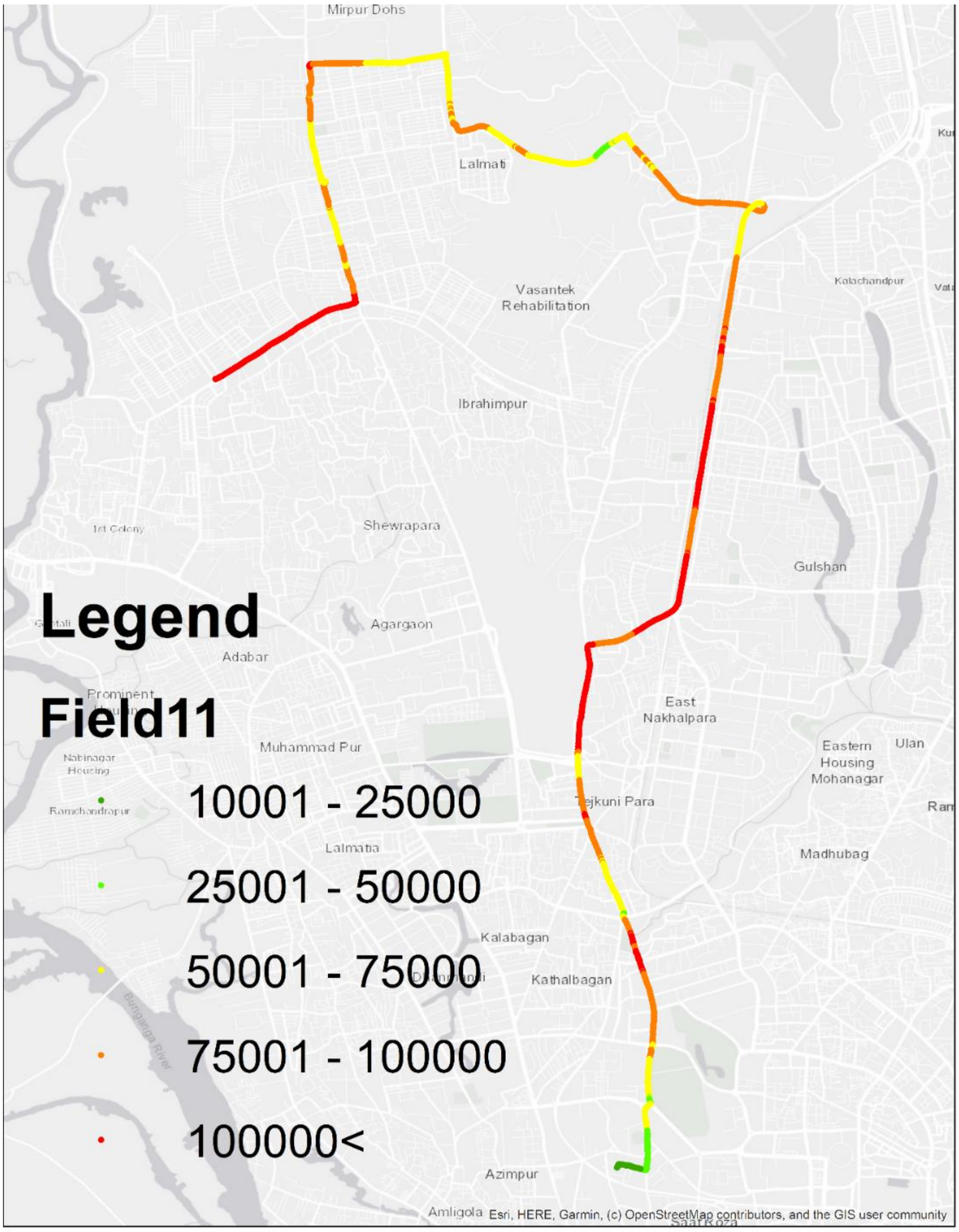

Figure C.33: Spatial variation of in-vehicle particle number concentrations measured in Private Car (Window Open) mode along the additional sampling route in Midday. Concentrations are averaged over 25 m road segments.

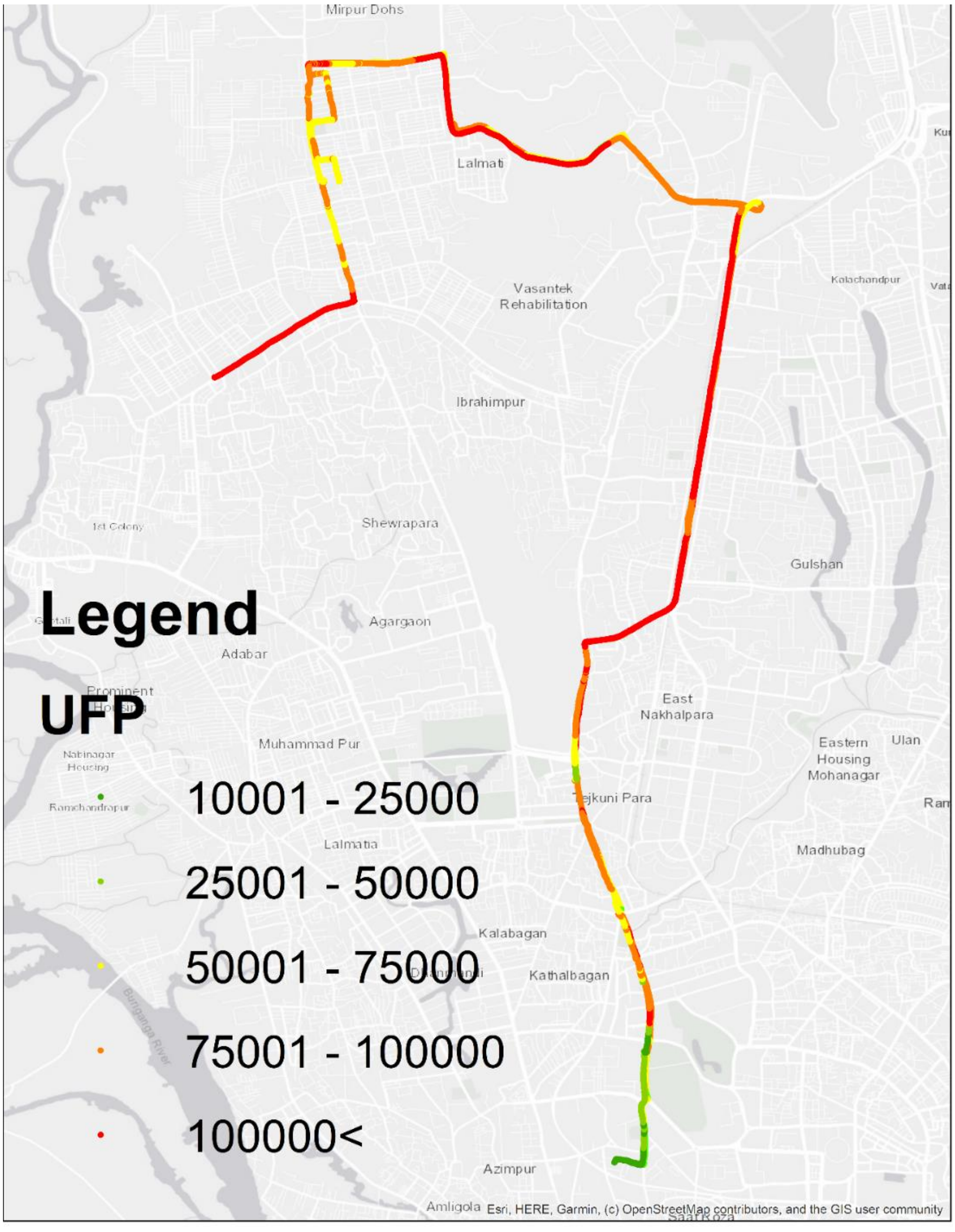

Figure C.34: Spatial variation of in-vehicle particle number concentrations measured in Private Car (Window Open) mode along the additional sampling route in the Afternoon. Concentrations are averaged over 25 m road segments.

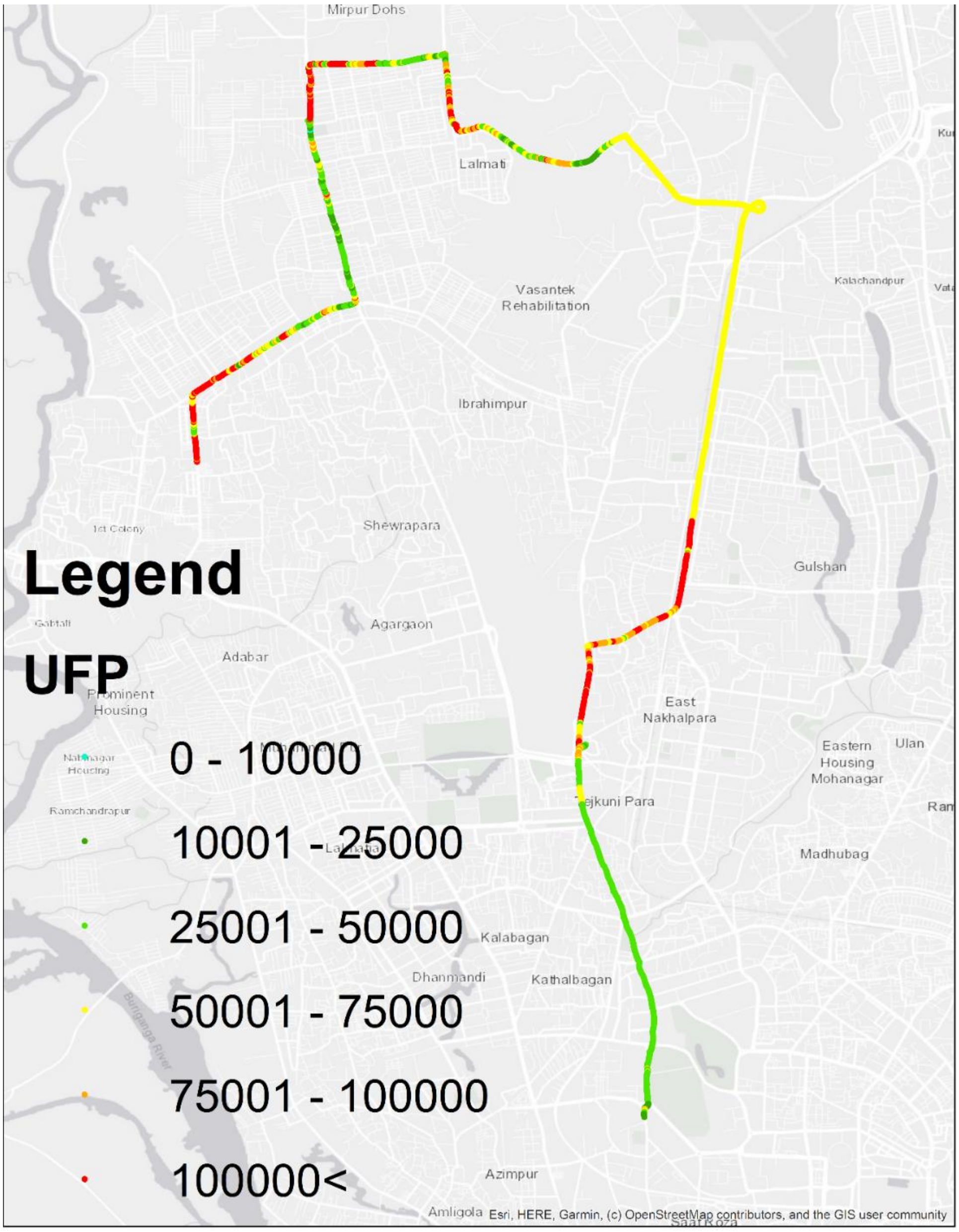

Figure C.35: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation OFF mode along the additional sampling route in the Morning. Concentrations are averaged over 25 m road segments.

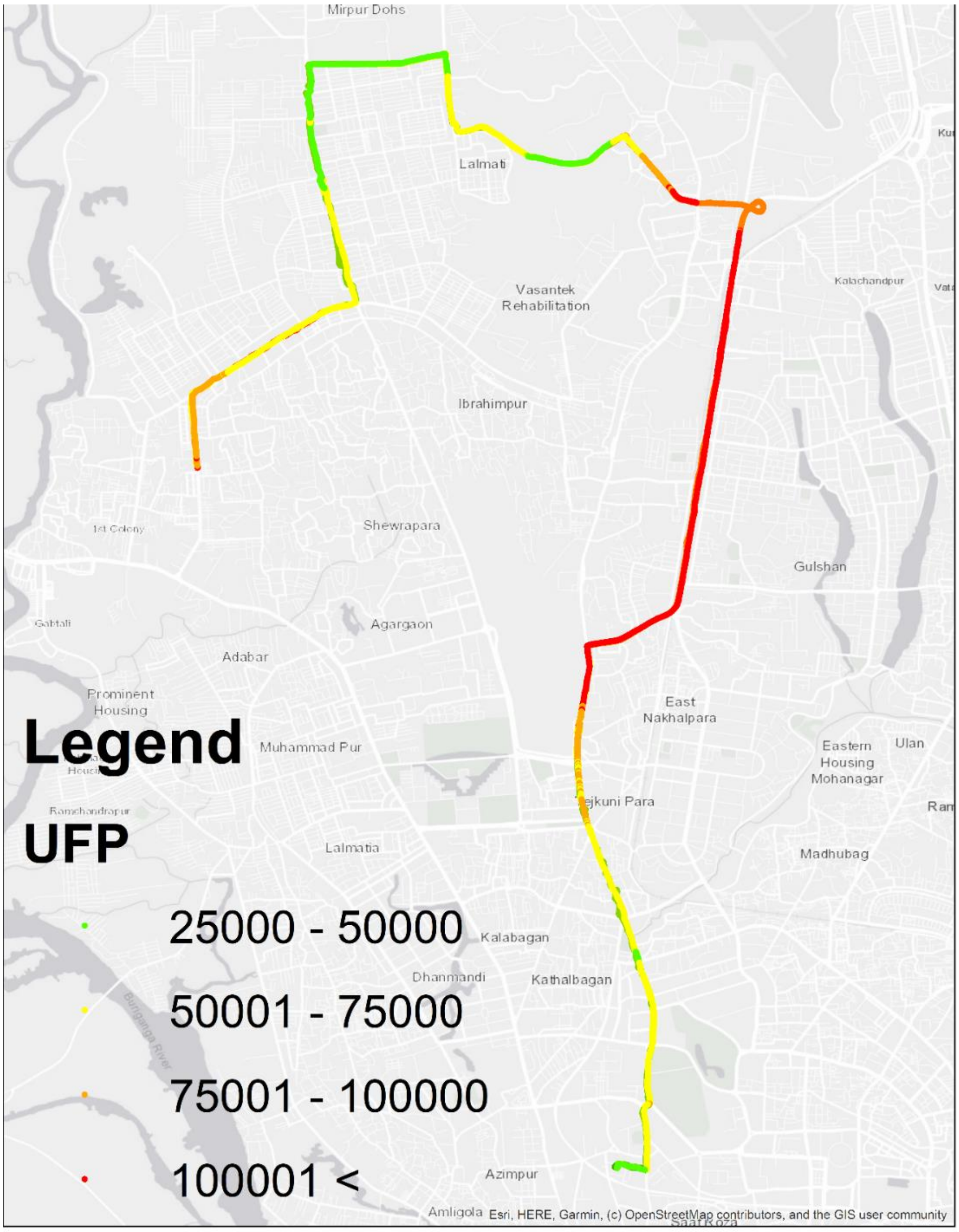

Figure C.36: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation OFF mode along the additional sampling route in Midday. Concentrations are averaged over 25 m road segments.

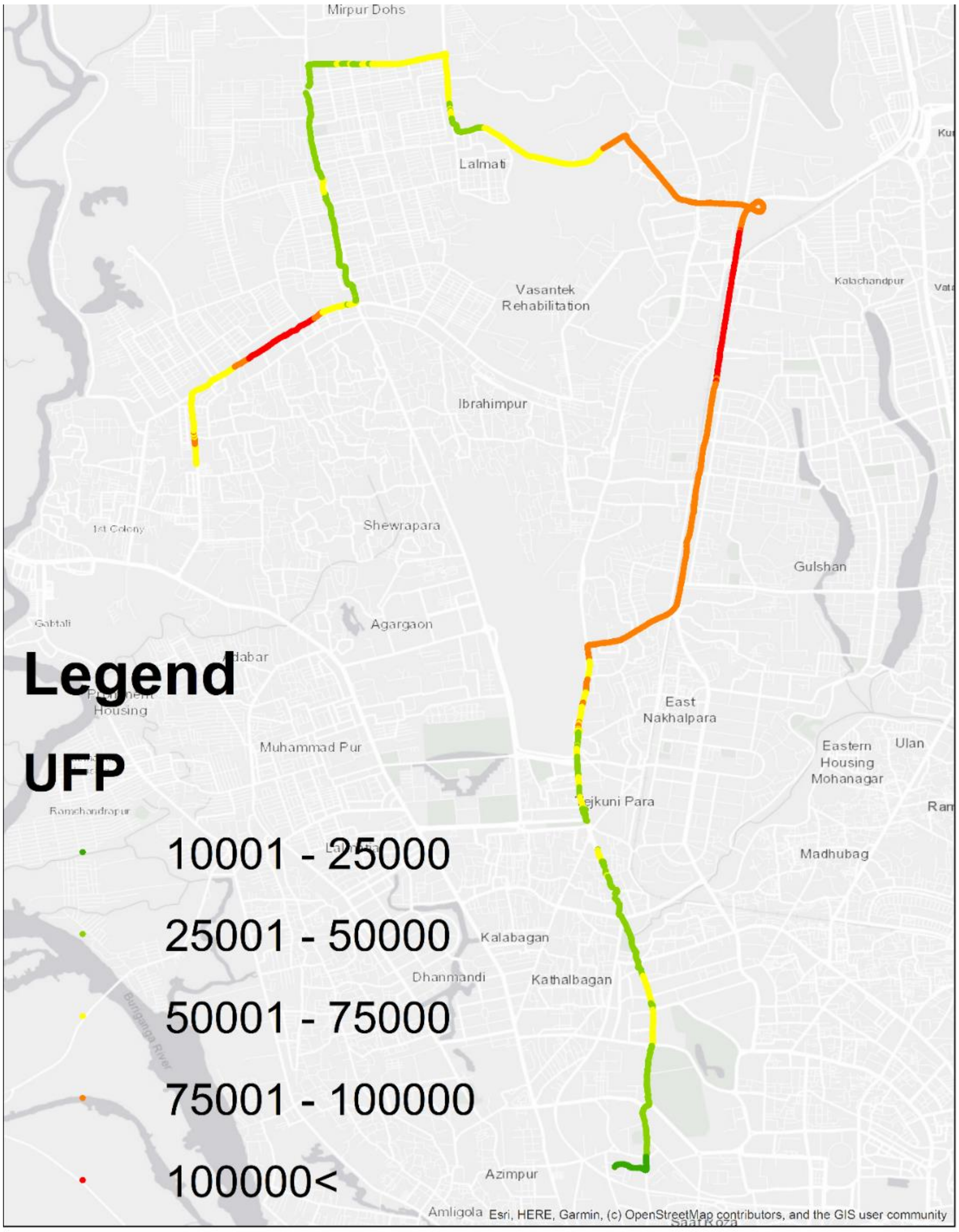

Figure C.37: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation OFF mode along the additional sampling route in the Afternoon. Concentrations are averaged over 25 m road segments.

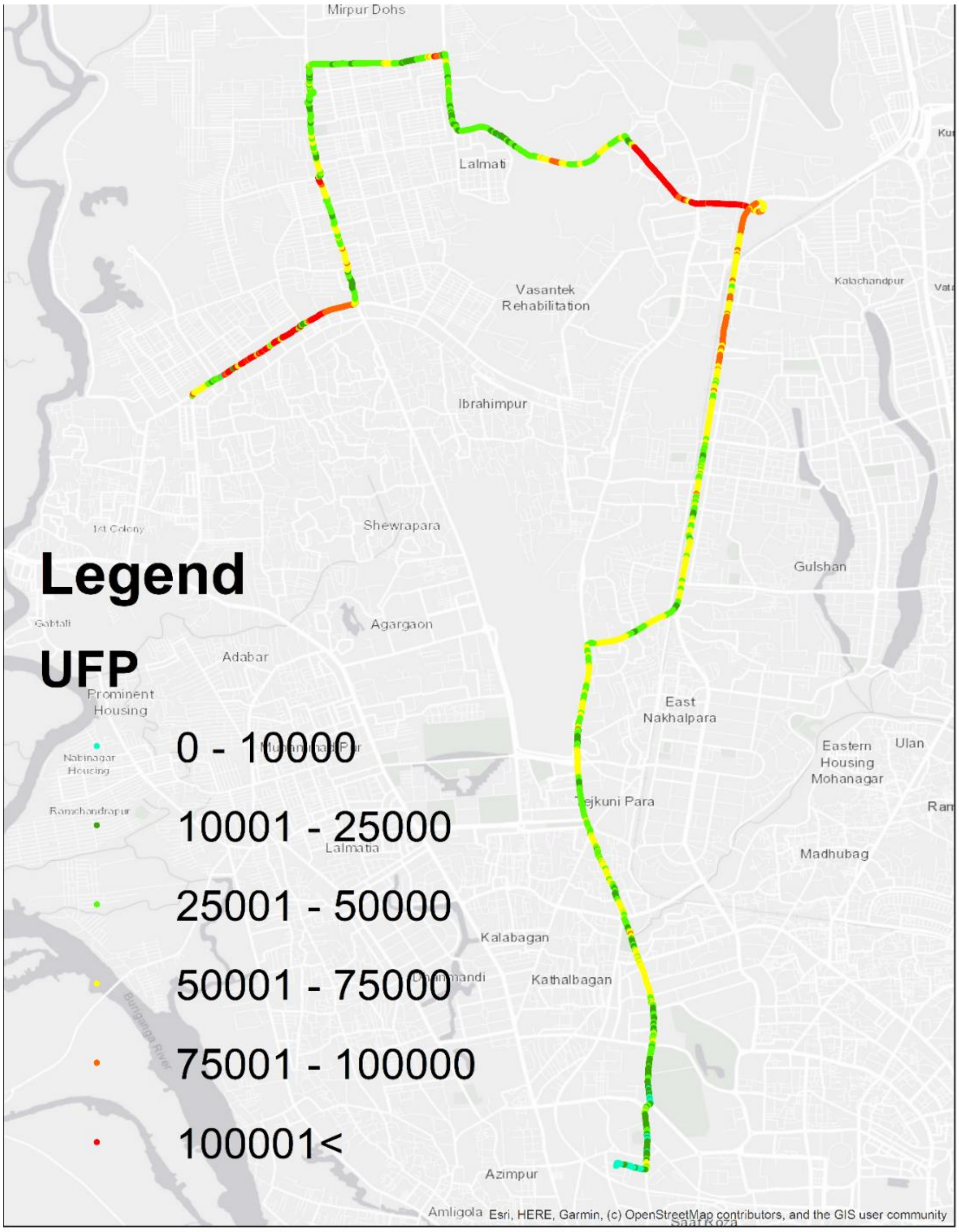

Figure C.38: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation ON mode along the additional sampling route in the Morning. Concentrations are averaged over 25 m road segments.

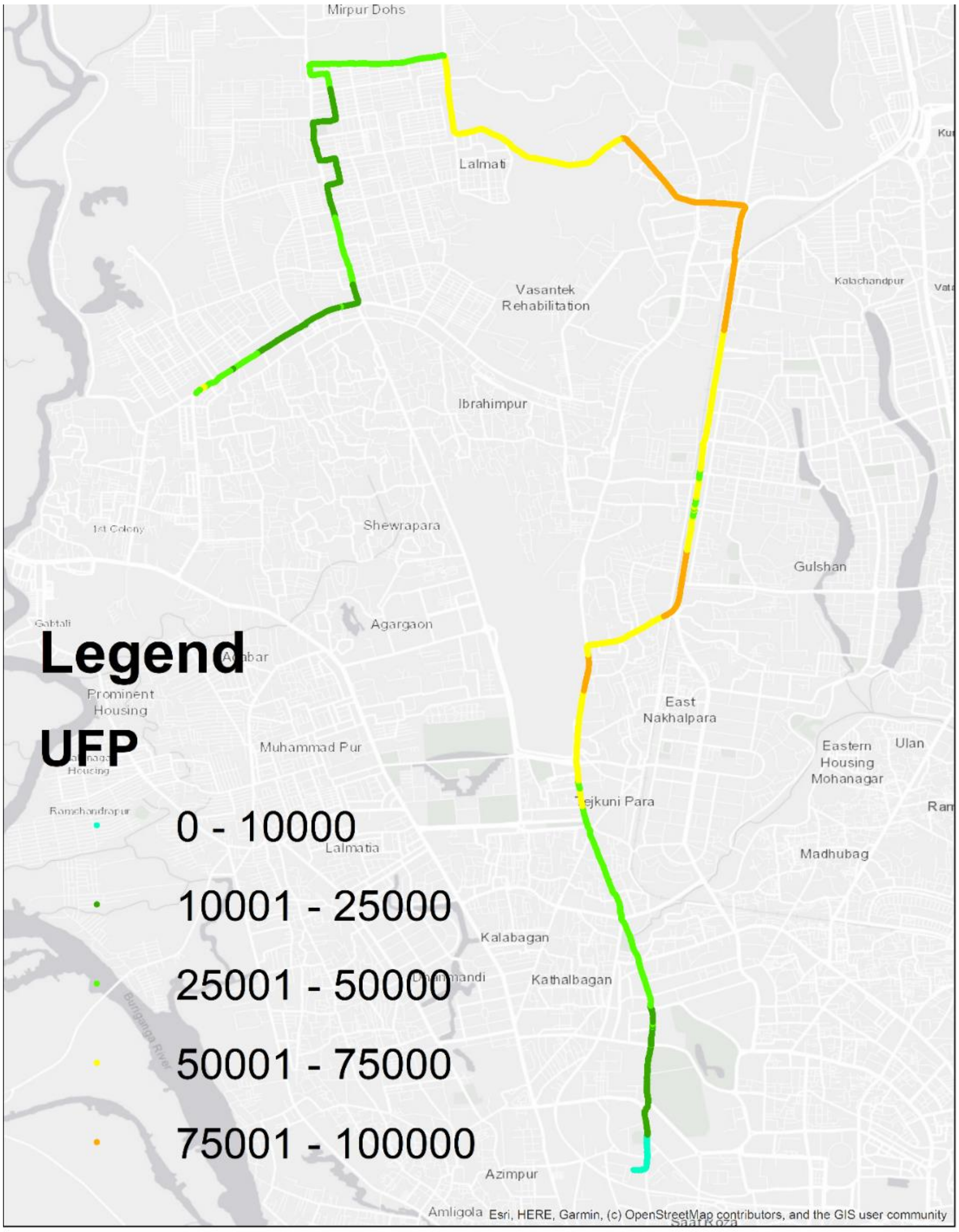

Figure C.39: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation ON mode along the additional sampling route in the Midday. Concentrations are averaged over 25 m road segments.

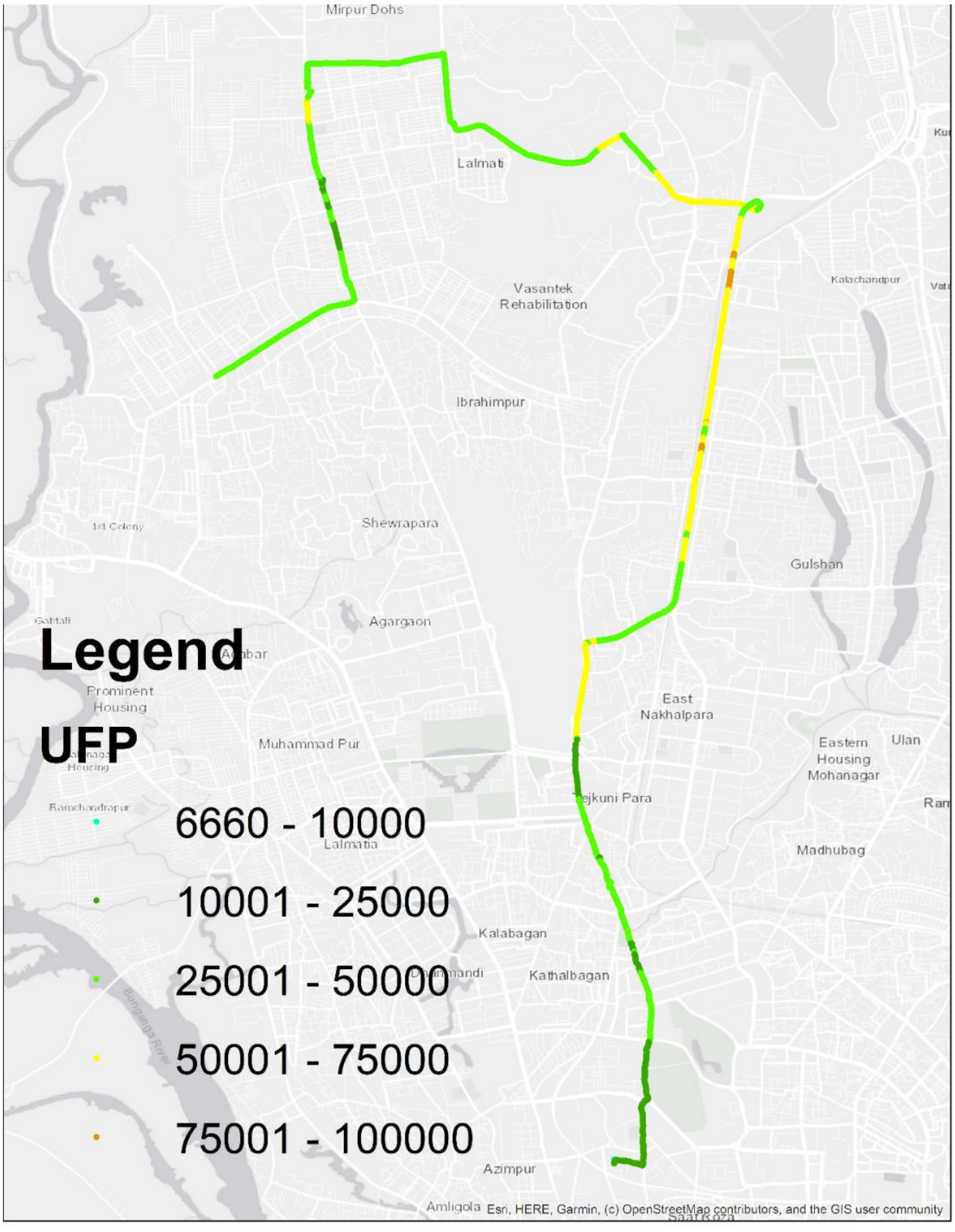

Figure C.40: Spatial variation of in-vehicle particle number concentrations measured in Private Car: Window Closed, Air Recirculation ON mode along the additional sampling route in the Afternoon. Concentrations are averaged over 25 m road segments.

APPENDIX-D: Summary of transportation modal choice and socio-economic profile of survey population

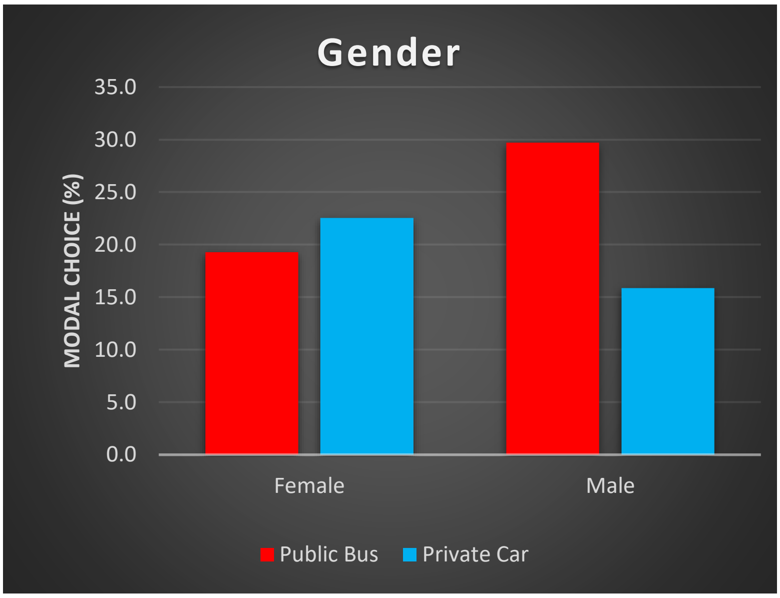

Figure D.1: Transportation modal choice by gender

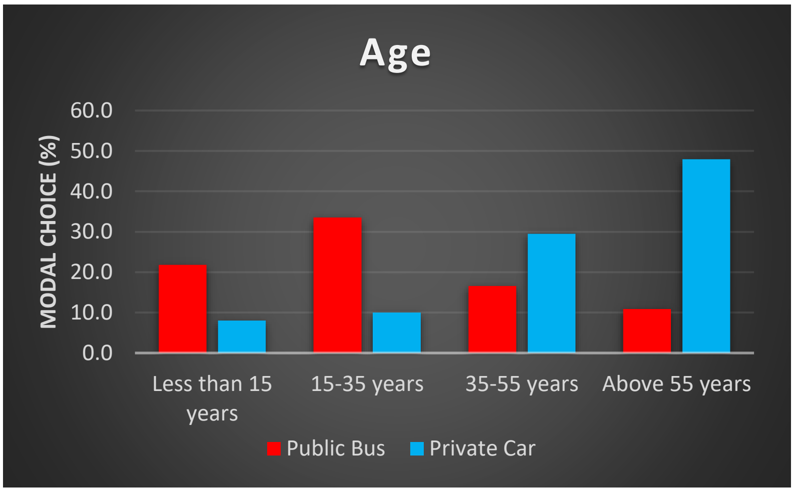

Figure D.2: Transportation modal choice by age

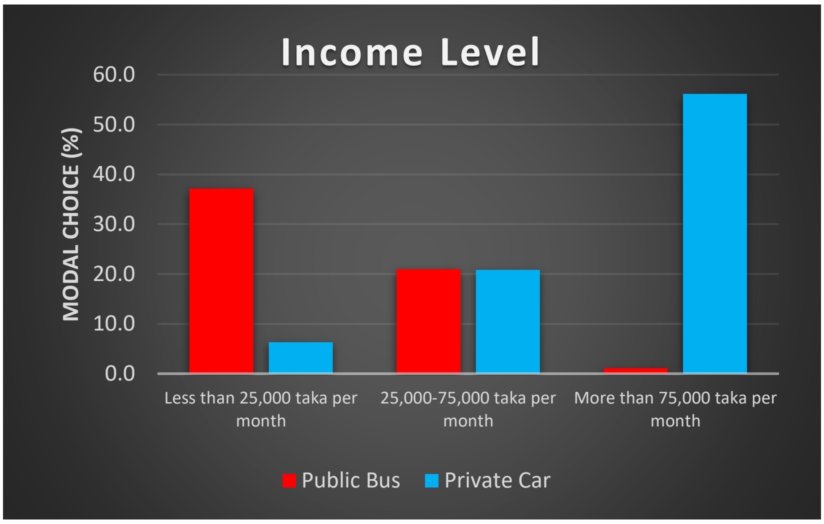

Figure D.3: Transportation modal choice by income level

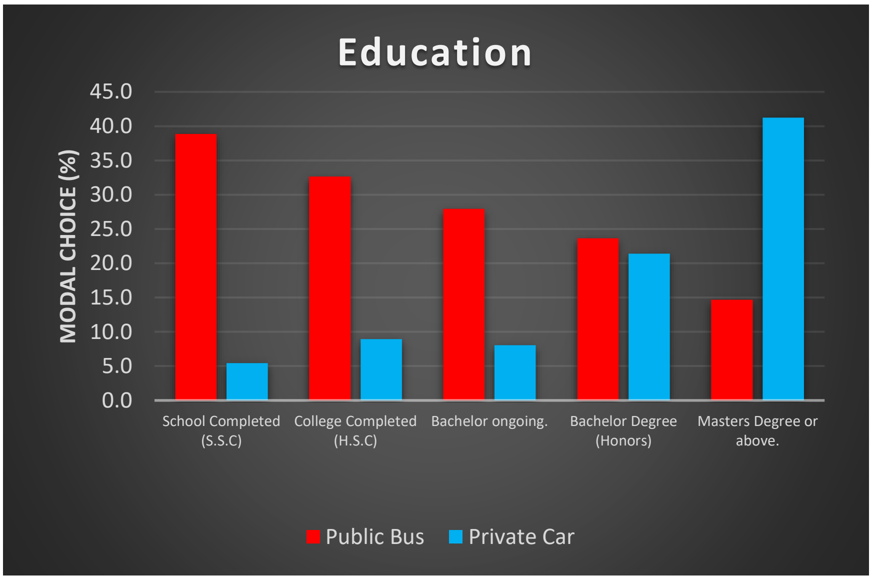

Figure D.4: Transportation modal choice by education level.