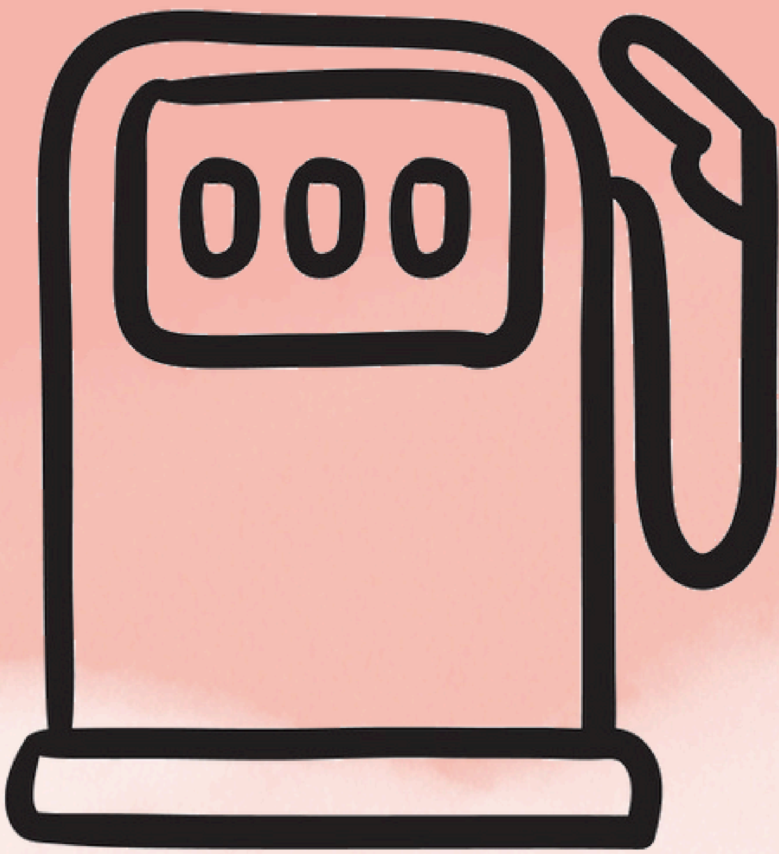
Fuel Station Survey (FuSS) to Profile In-use Vehicle Characteristics



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SIM-air working paper series #56-2025

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- Sharing knowledge on air pollution
- Providing science-based air quality analysis
- Promoting advocacy and raising awareness on air quality management
- Building partnerships among local, national, and international airheads

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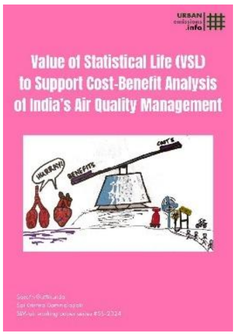

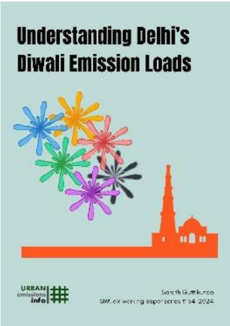

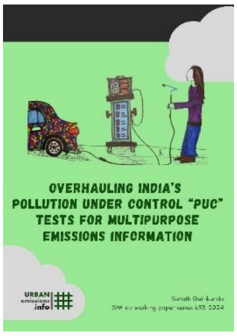

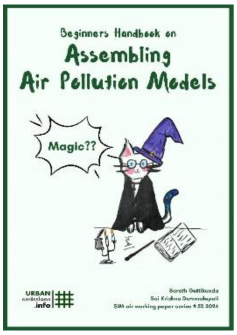

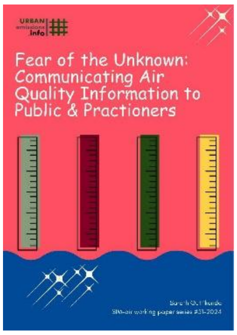

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Disclaimer

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List of Abbreviations

ADRI	Asian Development Research Institute
AQM	Air Quality Management
BSPCB	Bihar State Pollution Control Board
CNG	Compressed Natural Gas
CPCB	Central Pollution Control Board
FE	Fuel Economy
FuSS	Fuel Station Surveys
GIS	Geospatial Information Systems
IGP	Indo-Gangetic Plain
LMICs	Low- and Middle-Income Countries
LPG	Liquified Petroleum Gas
NO_2	Nitrogen Oxides
PM_{10}	Particulate Matter with diameter $< 10\ \mu m$
$PM_{2.5}$	Particulate Matter with diameter $< 2.5\ \mu m$
SUV	Sports Utility Vehicle
VEE	Vehicle Exhaust Emissions
VKT	Vehicle km Travelled

Short Story

Road transport is a major contributor to pollution in many urban areas worldwide, necessitating detailed data on in-use vehicles, including their age mix, usage, and fuel economy. This information is vital for developing a city's emissions baseline, offering insights into sources and intensities to design cost-effective, health-focused measures for sustainable air quality management.

In this paper, we present a framework for fuel station surveys (FuSS) to establish the vehicle characteristics necessary to build a localized emissions inventory. This approach addresses the challenges of traditional methods, which often require significant time, effort, and resources, causing delays in initiating groundwork, particularly in low- and middle-income countries.

The methodology is illustrated with an application in the city of Patna, India, where the survey for in-use vehicle profile was conducted by 19 trained students, over nine days and at ten fuel stations. The final cleaned sample size consisted of 9,775 vehicles, with 41% being 2-wheelers, 46% 4-wheelers, and 13% 3-wheelers and tempos. The fuel mix was 69% petrol and 31% diesel, with all motorcycles being petrol-powered.

The survey results specifically include age dependent vehicle mix for vehicle technology assessment, vehicle usage for assessment of km-traveled and fuel efficiency for energy intensity assessment. The methodology, tools, and training framework presented in this paper are adaptable and can be applied in settings beyond fuel stations and in other.

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1. Vehicle Exhaust Emissions

Urban environment is a complex mixture of aerosol and gaseous species originating from combustion sources like transportation, industries, residential cooking and heating and open waste burning, from non-combustion sources like dust from construction activities and resuspension on roads due to vehicle movement, and from natural sources like sea salt, lightning, windblown dust, volcanoes, and biogenic (Monks, Granier et al. 2009, Guttikunda, Goel et al. 2014, Guttikunda, Dammalapati et al. 2023). Modeling this ambient air pollution mixture to determine source contributions requires well-organized information on emission intensities from all sources, high-resolution meteorological data, and sufficient computational resources to host models and store data. While advancements in cloud computing have optimized computational costs for most state-of-the-art modeling applications, building a comprehensive and accurate emission inventory remains a significant challenge in the low- and middle-income countries (Schwela, Haq et al. 2006, Sokhi, Moussiopoulos et al. 2021, Gani, Pant et al. 2022, Garland, Altieri et al. 2024, Khan, Kumar et al. 2024).

Among the known emission sources, road transport is the most data intensive—starting with a clean database of vehicle numbers by technology and fuel type, their usage characteristics, emission intensities, and algorithms to disaggregate the total emissions into grids and over time (Solazzo, Crippa et al. 2021, Wallington, Anderson et al. 2022, Guttikunda 2024, Lekaki, Kastori et al. 2024). Availability of information in such detail is higher in the European countries, in the United States, and in some big cities of Asia and Latin America like Beijing, Shanghai, Delhi, Singapore, Bangkok, Bogota, and Sao Paulo, but openness and availability of this data in small and medium sized cities in the low- and middle-income country is scarce (Deng, Lv et al. 2020, Gräbe and Joubert 2022).

Figure 1: Typical equation to calculate vehicle exhaust emissions

A typical equation to calculate on-road vehicle exhaust emissions (VEE) is a product of three numbers – number of vehicles (supply side of the problem defined as the number of vehicles on the road), vehicle usage (demand side of the problem, often measured as vehicle km travelled—VKT), and an emission factor (technology side of the problem, often measured as gm of pollutant emitted per km) (Schipper, Banerjee et al. 2009, Guttikunda and Mohan 2014). A version of this equation is applied in established VEE models like IVE[1], MOVES[2], and COPERT[3] with applications worldwide (Davis, Lents et al. 2005, Koupal, Beardsley et al. 2010, Samaras , Ntziachristos et al. 2016, Mądziel 2023). Complexity of this equation multiplies exponentially with the increase in the types of vehicles, types of fuels, age-mix of the vehicles, usage of the vehicles, fuel economy of the vehicles, travel patterns in the city, types of roads, road conditions, and driver behavior (Baidya and Borken-Kleefeld 2009, Sadavarte and Venkataraman 2014, Sahu, Beig et al. 2014, Nagpure, Gurjar et al. 2016, Jaiprakash, Habib et al. 2017, Saikawa, Trail et al. 2017, Hakkim, Kumar et al. 2021, Böhm, Nanni et al. 2022, Singh, Mishra et al. 2022, Lekaki, Kastori et al. 2024). Some of these variables are collectively referred to as in-use vehicle characteristics (Goel, Guttikunda et al. 2015, Guttikunda 2024).

Important characteristics to keep note of when building the VEE inventory are

1. The number of vehicles on the road (supply-side) is not the same as the number of vehicles registered in the city (for the study year). These numbers must be adjusted to determine what fraction of the registered vehicles are considered in-use (on the roads) and contributing to the emission loads every day. This is often achieved via the use of survival functions (Zachariadis, Samaras et al. 1995, Guttikunda 2024)
2. The vehicle-usage (demand-side) varies with vehicle type and age. This in-use characteristic determines the contributions of various vehicle types by age to the city's total emission load. The typical assumption is that older vehicles travel less
3. The fleet-average emission factor (technology-side) is directly influenced by the in-use fuel economy of the vehicles. Typically, it is assumed that older vehicles have lower fuel economy, leading to higher fleet-average emission factors.

In the emission inventory studies, these characteristics must be customized for building a localized emissions inventory.

To determine a representative set of these numbers, multiple surveys must be conducted across various locations, times, and conditions. However, this process involves significant expenses, as large-scale data collection requires funding for logistics, equipment, and technology. Conducting these surveys demands expertise in survey design, data collection techniques, and statistical analysis to ensure reliable and accurate results, as well as a well-coordinated team to

[1] IVE – International vehicle emissions model - http://www.issrc.org/ive
[2] MOVES and Mobile Source Emissions Research - https://www.epa.gov/moves
[3] COPERT - https://copert.emisia.com

manage personnel-intensive tasks such as field operations, data entry, and subsequent analysis. In low- and middle-income regions, where data gaps for such studies are most significant, these requirements often result in no surveys being conducted, with most analyses relying solely on reference literature reviews.

In this paper, we present a rapid-assessment survey framework called fuel station surveys (FuSS) to profile the necessary in-use vehicle characteristics in a city. This framework addresses and overcomes the common challenges of traditional large-scale surveys, enabling quick replication and repeatability of the process to ensure that vehicle characteristic information remains as up to date as possible.

2. Case Study City: Patna, India

Patna (capital city of Bihar, India) has a population of 1.3 million, is spread over 72 wards, is located on the Indo-Gangetic plain (IGP) and is largely supported by agricultural activities. In 2023 world ranking, Patna was ranked 20^{th} most polluted city with an annual average $PM_{2.5}$ concentration of 82 $\mu g/m^3$ (https://iqair.com), which is 16 times more than the World Health Organization guideline of 5 mg/m^3. This is an improvement of 30% compared to 2017's annual average, in part because of promotion of clean fuels like liquified petroleum gas (LPG) and electricity for residential and commercial cooking and introduction of the best available vehicle and fuel standards (Bharat 6, equivalent of Euro 6) in 2020.

Road transport continues to be one the main contributors to ambient $PM_{2.5}$ pollution in the city, along with residential and commercial cooking, heating in the winter months, open waste burning, emissions from point sources like the 300-brick kilns surrounding the city, and dust from construction activities and resuspension on the roads (Guttikunda and Jawahar 2014). On IGP, Patna city is an important commercial hub with multiple highways crisscrossing, leading to movement of many freight vehicles through the city boundary every day. Emission inventory and chemical transport model-based studies estimated up to 30% of the annual average $PM_{2.5}$ originating from road transport (BSPCB 2019).

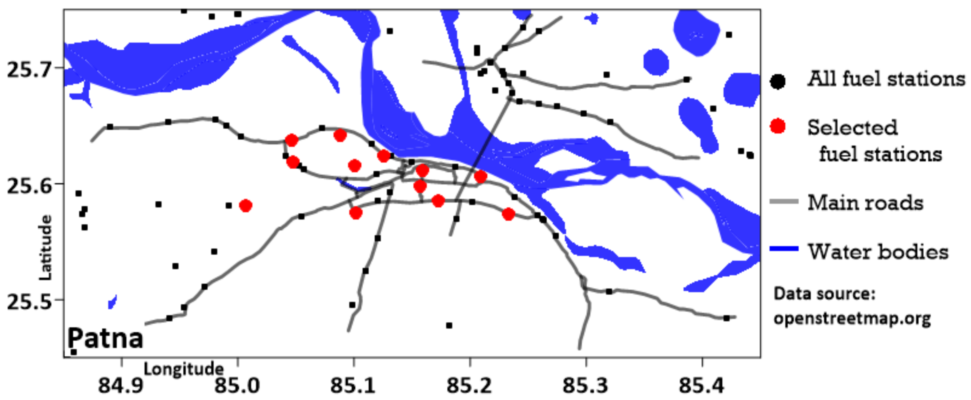


Figure 2: Location of the ten selected FuSS survey stations (red dots) and all the fuel stations (black stations) in Patna city's airshed

According to the Ministry of Road Transport and Highways, total registered vehicle fleet in Patna is approximately 2 million in 2023, with 70% two-wheelers (including mopeds, scooters, and motorcycles), 13% passenger four—wheelers including taxis, 7% three—wheelers for passengers and freight, 4% heavy duty and light duty vehicles, and rest covering public, contract, school, and private sector buses, para-transit vehicles, and non-road vehicles. Para-transit vehicles can carry three to ten passengers per trip, mostly covering short distances, and operate in dual fuel mode using petrol and compressed natural gas (CNG) or diesel and CNG. With dust resuspension from vehicle movement on the roads, road transport contributes up to 40-50% of $PM_{2.5}$ pollution in parts of the city.

3. Fuel Station Survey (FuSS)

Fuel Station Survey (FuSS) in Patna was conducted in August 2018 and coordinated by Urban Emissions (New Delhi, India) and Asian Development Research Institute (ADRI, Patna, India)

Why fuel stations?

The assumption here is that irrespective of a vehicle's age or condition, if it is in-use, it will visit a station for refueling and their survey will represent the profile of in-use vehicles of the city.

The key survey outputs which serve as direct inputs in the VEE calculations are

1. the age-mix of the in-use vehicles by type. This profile can be overlayed with vehicle sales information to construct survival functions. The survival functions can be overlayed with the registered number of vehicles to estimate the volume of in-use vehicles in the city
2. Variation in vehicle usage (VKT) with age and type – usage functions can be constructed for future calculations
3. Variation in the fuel economy with age and type – consumption patterns can be constructed with age and correlated with manufacturing reports for future calculations.

An important limitation of this framework is the mix of vehicles at the fuel stations. This mix will include vehicles registered in the city and those visiting from the neighboring districts or states. While the km-traveled and fuel economy rates are relevant for building the in-use characteristics, the total emission calculations for the city must include an additional factor for vehicles not registered in the city. This is often accomplished with the use of the receipts from the toll booths at the city's entry and exit points.

Number of stations for survey

A list of operational fuel stations was extracted from https://openstreetmap.org and of the total mapped 90 stations, ten stations (approximately 10%) were selected for the FuSS application (**Figure 2**).

Conducting the survey at a greater number of stations is always desirable, as it enhances the representativeness of the data by capturing a broader range of vehicles and usage patterns across different locations. Randomized selection further helps capturing various landuse types in the city ranging from residential, traffic, commercial, to industrial.

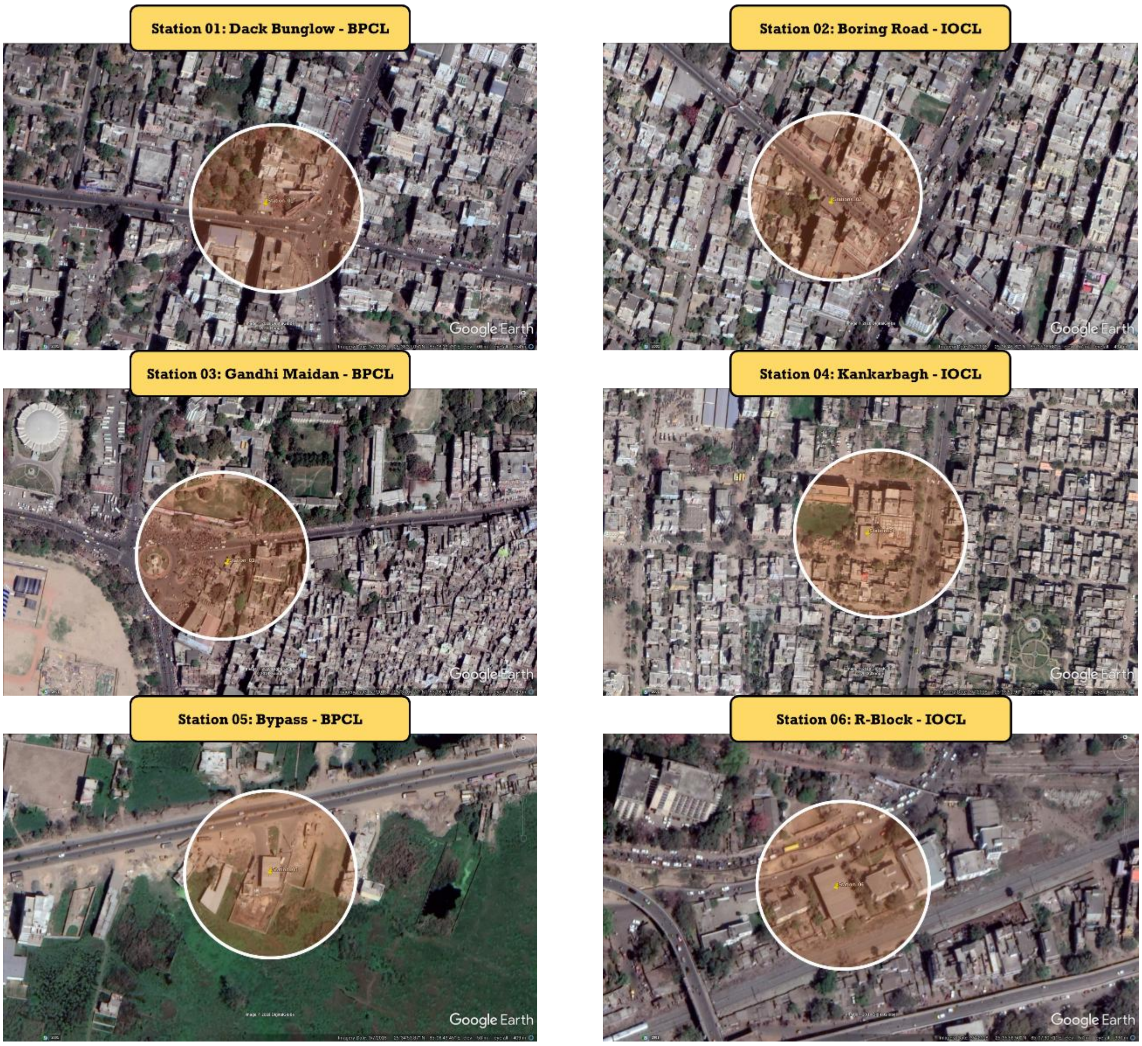
A limitation of this survey is the location of the fuel stations. The surveys conducted at the stations within the city limits will mostly capture the passenger vehicles registered in the city and the surveys conducted at the stations outside the city limits will also capture freight vehicles and a mix of vehicles not registered in the city, often passing through the city-limits. Application in Patna was limited to the city administrative boundary capturing mostly passenger vehicles.

Station			
1	Dack Bunglow	BPCL	934
2	Boring Road	IOCL	1468
3	Gandhi Maidan	BPCL	574
4	Kankarbagh	IOCL	2115
5	Bypass	BPCL	762
6	R-Block	IOCL	1716
7	Ashok Rajpath	BPCL	479
8	Gaya line Gaumati	BPCL	464
9	NH30	BPCL	461
10	Bailey Road	BPCL	1345
		SUM	10318

SUM		
BPCL	5019	49%
IOCL	5299	51%
	10318	

IOCL = Indian Oil
BPCL = Bharat Petroleum

Figure 3: Location of the ten selected FuSS survey stations (red dots) and all the fuel stations (black stations) in Patna city's airshed



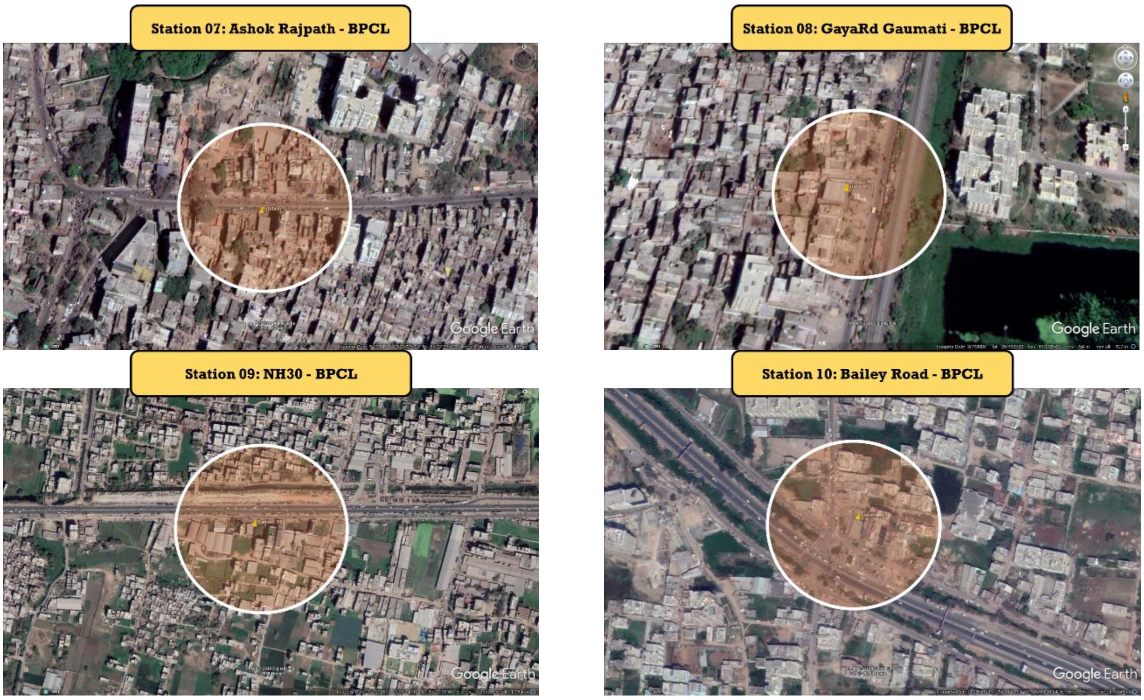


Figure 4: Google Earth snapshots of survey locations

According to the guidelines of the Central Pollution Control Board (CPCB, New Delhi) for ambient pollution monitoring, the selection of monitoring locations must include a diverse mix that represents residential, industrial, roadway, and background activities. This ensures a comprehensive understanding of air quality across different environments and captures the variation in pollution levels associated with distinct land-use and activity types (CPCB 2003). A similar approach was taken for the selection of the survey stations to capture a mix of activities. The station location and operator's information is presented in **Figure 3** and Google Earth snapshots of the locations showing their surroundings are presented in **Figure 4**. Three stations are owned by Indian Oil and seven by Bharat Petroleum. Permissions were obtained to conduct the survey at these select stations with the help of the Bihar State Pollution Control Board and ADRI staff.

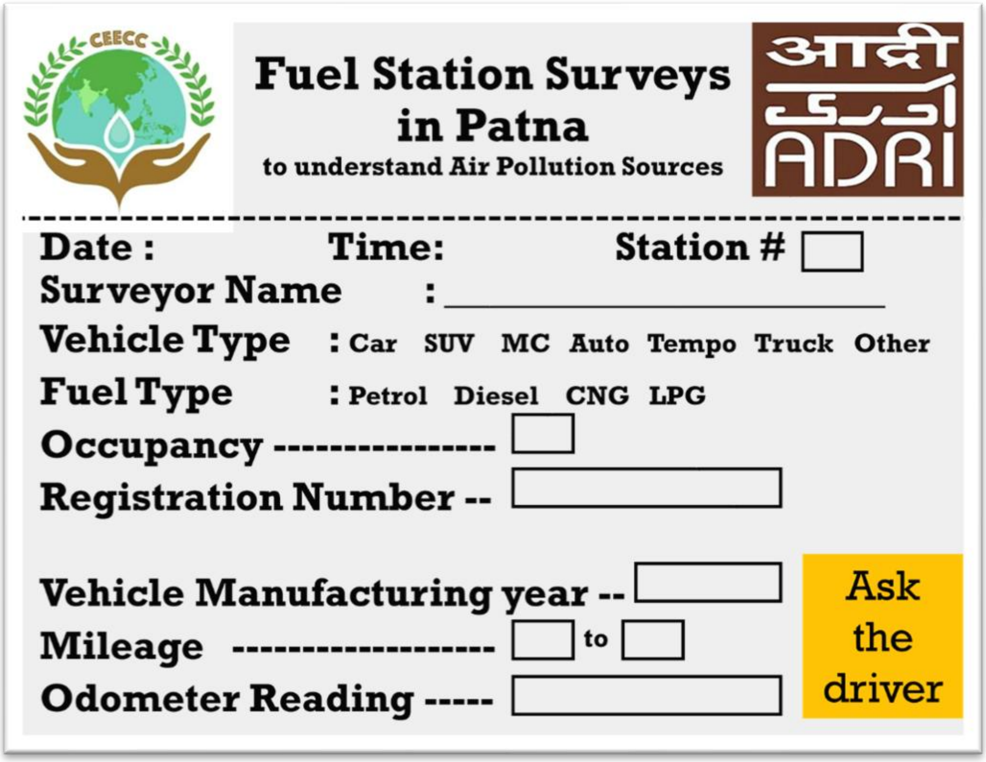
Survey questionnaire

The questionnaire is kept to a minimum, so that the questions to ask the driver or the owner of the vehicle can be accomplished in less than 2-3 minutes – this is the average time taken to fill the fuel tank.

A summary of the data points collected per survey is shown in **Table 1**. There is some waiting period for the vehicles in line to reach the fuel pump, which is often used to the surveyor's advantage to explain why the survey is being conducted and to provide clarifications on how the data is used for emissions and pollution analysis.

Table 1: A sample FuSS survey questionnaire

	Data point collected	Action point
1	Date, time, & station number	Observed
2	Surveyor name	Observed
3	Vehicle type (2-3-4-wheeler, tempo, truck, bus)	Observed
4	Fuel type (petrol, diesel, CNG)	Observed
5	Occupancy	Observed
6	Vehicle registration number	Observed
7	Vehicle manufacturing year	Asked
8	Odometer reading	Asked
9	Fuel economy (mileage)	Asked


Fuel Station Surveys in Patna
to understand Air Pollution Sources

Date : Time: Station #

Surveyor Name :

Vehicle Type : Car SUV MC Auto Tempo Truck Other

Fuel Type : Petrol Diesel CNG LPG

Occupancy ----------------

Registration Number --

Vehicle Manufacturing year --

Mileage ------------------- to

Odometer Reading -----

Ask the driver

Figure 5: Google Earth snapshots of survey locations

Every questionnaire involved three surveyors. One at the fuel pump asking the three questions, one noting answers to questions which can be observed, and one crosschecking the entries and answering any questions from the driver. This reduced the overall interaction time with the driver and made room to address any survey-related queries. Only in a few instances, the conversations were longer than 10 mins with an enthusiastic citizen who wanted to know more about the study and the use of the data collected during the survey. Keeping the questionnaire simple and to a minimum increased the overall success rate of the data collection (>95% response rate). Most of the non-response cases were because the driver was in a rush and didn't want to engage in a conversation.

The questionnaire was programmed into an open-source data management software ODK. This app-based survey was designed to enable immediate digitization of the survey points, extract data for rapid statistical analysis, and track progress of data collection from day to day. Tracking of the number of surveys conducted at each station was useful in advising the surveyors, at the start of the next day, on which fuel type and vehicle type to target that day, to capture a good mix of vehicles in the survey. A presentation with screenshots of data-entry steps from the ODK application is included in the supplementary material.

A limitation of this survey, compared to large-scale travel demand surveys used for urban transport planning or traffic demand management, is the grouping of vehicles into broad categories such as cars, SUVs, motorcycles, 3-wheelers, and tempos. This approach is intentional, as the survey is designed for rapid assessment, ensuring it can be completed anonymously within three minutes without requiring access to vehicle registration cards or detailed manufacturing information. (Guttikunda 2024) presents a detailed methodology describing the standardized fleet categories in India and how the clubbing to broader categories for emission calculations is operationalized.

Survey sample size

A large sample size is desirable. Target sample size was at least 1% of the registered passenger vehicle fleet in the city, which is at least 10,000 surveys in 2018. At the end of the survey period, a total of 10,318 surveys were conducted and the final cleaned full dataset included 9,775 survey points. Some of the surveys were discarded for mixed reasons ranging from broken odometers, unreasonable reporting of fuel economy rates, and not knowing the manufacturing year (for example, in cases where the driver is not the owner of the vehicle).

A practical metric for concluding the survey was the increasing frequency of repeat customers at the fuel stations, which typically occurred by the fourth or fifth day. At this point, the surveys collected were tallied, and the team was relocated to another station to continue data collection.

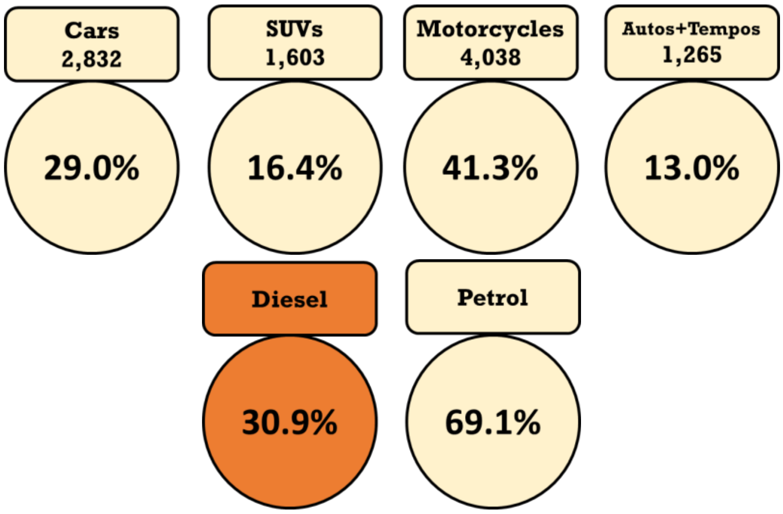


Figure 6: Summary of survey points collected

Survey training

The availability of trained surveyors is one of the constraints for increasing the sample size. Nineteen students from local colleges and universities participated in the survey, who were interning at ADRI as part of a summer environmental career development course. Before the survey, all the students were engaged in a two-day training course covering the aspects of air pollution and health, emissions and pollution modeling, data requirements, data availability, pollution management, and discussions specific to road transport emissions modeling[4]. The course covered basic information necessary to answer any inquisitive questions like (a) what is the biggest contributing source of air pollution in the city? (b) is transport the main cause of air pollution in the city (c) why are we doing the emissions analysis and (d) how are we going to use the data collected to carry out emissions and pollution analysis. The training and capacity building included a session on dos and don'ts during the survey:

1. Always be courteous to the driver and the owner.
2. On the phone – (a) test the logins and passwords before doing the actual collection (b) check battery and space to avoid any crashes in the middle of the survey and (c) adjust the screen light to show the entries properly.
3. Strictly no demanding information. If the driver or the owner does not want to participate, then stop. If he/she agrees to answer all or part questions, then proceed. We want information only if they participate voluntarily.
4. Strictly no putting your head inside the car for the odometer reading or asking for the vehicle registration card. All numbers are noted only if the driver or the owner participates voluntarily.
5. Strictly no taking surveys outside the designated area of the fuel station.
6. For any random entry, use the word "TEST" for the vehicle registration number. This will help eliminate random entries from the final database.

A mock survey was conducted in the lab to get familiar with the questioning and the app for entering data. The first day of the survey was conducted with everyone at one station only, where three students followed the survey procedures, while others observed it on the side.

[4] An updated set of course material is available open access at https://urbanemissions.info/tools along with instructional videos, primers, working papers, and presentations.


GO


GO



B.P.- PATNA



4. Patna's Survey Results

Data entry lessons: App or Paper?

A very important cultural lesson at the start of the survey was regarding the ODK app. There was hesitation among the drivers and the owners to participate in the survey, when the data was entered directly into the app at the fuel pump. They wanted to participate but also wanted the surveyor to write down the answers, instead of entering in the app. Response rate at this hour was less than 50%. After an hour on day-one, the data entry process was shifted to paper. This dramatically increased the participation rate.

At the end of each survey day, surveyors entered all the data points into the app and uploaded them to the central repository for processing. This helped keep the pace of the survey as planned, for collection and analysis.

Sometimes a driver was not able to answer the question on fuel economy with a single number. Instead, answers included "I put 5 liters of diesel in the morning and run for 150 km in a day, "I get 12 km/lit in the city and 16 km/lit outside the city" or "I get 12 km/lit when running with AC and 16 km/lit without AC"). These numbers were noted as ranges.

Patna's in-use vehicle characteristics

A summary of the survey results is presented in **Table 2-4** and **Figure 7**. The survey was conducted over nine days, at ten fuel stations, using 19 students. The final cleaned sample size was 9,775 with 41% covering all 2-wheelers, 46% covering all 4-wheelers, and 13% covering 3-wheelers and tempos. The fuel mix of vehicles was 69% for petrol and 31% for diesel. All motorcycles are petrol based.

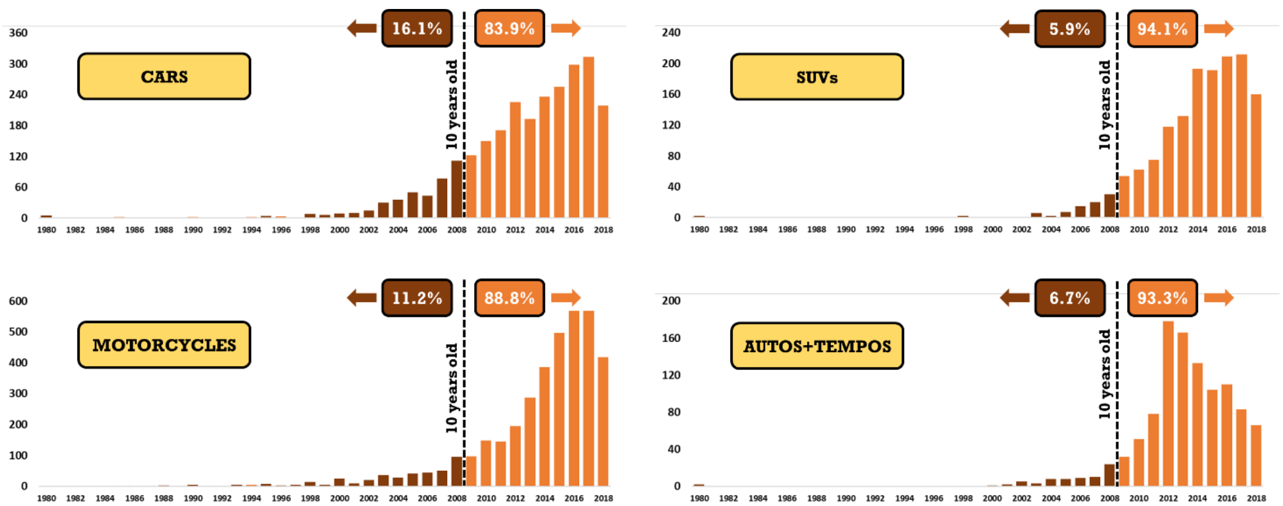


Figure 7: Age-mix of vehicles surveyed in Patna, India. SUVs are sports utility vehicles, larger 4-wheelers, often running on diesel. X-axis represents the manufacturing year and the Y-axis represents the sample size for each manufacturing year.

The age-mix information is crucial for building the survival functions – to know the probability of a vehicle to continue to be in-use on the roads (**Figure 7**). (Guttikunda 2024) presents a summary and an application of these survival functions for India's vehicle stock at national, state, and city level.

Table 2: Summary of FuSS in Patna, conducted in August 2018. SUVs are sports utility vehicles, larger 4-wheelers, often running on diesel

	Sample size	Age-mix				Fleet avg	Fleet avg
		0-5yr	6-10yr	11-15yr	>15yr	age	Odometer (km)
Cars	2832 (29%)	50.8%	33.1%	12.3%	3.8%	5.9yr	9,500
SUVs	1603 (17%)	64.5%	29.5%	4.9%	1.0%	4.5yr	14,500
Motorcycles	4038 (41%)	65.4%	23.4%	7.1%	4.1%	4.9yr	7,000
Autos-Tempos	1265 (13%)	46.2%	47.1%	5.5%	1.2%	5.3yr	15,000

Table 3: Statistical summary of vehicle usage data (as vehicle km traveled) from FuSS in Patna. SUVs are sports utility vehicles; Cars and SUVs include larger 4-wheelers running also as taxis and often diesel-based

	Cars		SUVs		Motorcycles	Autos-Tempos	
	Petrol	Diesel	Petrol	Diesel	Petrol	Petrol	Diesel
Sample share by fuel	76%	24%	7%	93%	100%	31%	69%
% vehicles with VKT/yr							
< 5000 km	30%	14%	20%	9%	37%	14%	11%
5000-10000 km	41%	33%	38%	29%	44%	26%	21%
10,000-20,000 km	21%	33%	26%	39%	14%	43%	38%
20,000-30,000 km	5%	13%	6%	14%	2%	11%	15%
>30,000 km	3%	8%	11%	9%	2%	6%	14%
Average (km)	9,400	14,000	14,200	15,200	8,100	13,700	18,200
Standard Deviation (km)	9,300	11,400	16,500	11,000	9,200	9,300	16,700
95th Percentile (km)	25,600	34,200	49,900	35,400	17,900	32,600	46,300
Median (km)	7,000	10,800	8,600	12,500	6,000	11,800	13,900

Table 4: Statistical summary of fuel efficiency data (average ± standard deviation) from FuSS in Patna. SUVs are sports utility vehicles; Cars and SUVs include larger 4-wheelers running also as taxis and often diesel-based

	Cars		SUVs		Motorcycles	Autos-Tempos	
Km/liter	Petrol	Diesel	Petrol	Diesel	Petrol	Petrol	Diesel
Pre-1990	12.9 ± 2.8				35.4 ± 11.7		
1991-2000	12.1 ± 2.9	12.5 ± 2.5		12.6 ± 3.8	40.4 ± 14.4		
2001-2010	13.1 ± 3.9	14.8 ± 4.2	12.0 ± 2.2	11.1 ± 2.4	45.2 ± 10.7	21.7 ± 4.8	22.5 ± 3.8
Post-2010	13.9 ± 3.5	15.3 ± 3.5	13.5 ± 4.6	12.0 ± 2.9	42.2 ± 9.6	21.5 ± 5.1	23.4 ± 4.8
All fleet -							
Average ± SD	13.6 ± 3.7	15.2 ± 3.6	13.3 ± 4.5	11.8 ± 2.9	42.7 ± 9.8	21.6 ± 5.1	23.3 ± 4.5
95th Percentile	20.0	20.0	20.0	17.0	60.0	30.0	30.0
Median	13.0	15.0	12.0	12.0	40.0	20.0	23.0

On average, 90% of the vehicles surveyed are under 10 years of age, with a fleet average age between 4.5 years for SUVs and 5.9 years for cars. This information is an important input for answering policy relevant questions. For example: what are the impacts of banning vehicles older than 10 years or 15 years? Is it cost-beneficial to implement such a measure, if the older fleet size is too small to track and manage? Is it cost-beneficial to instead implement a stricter inspection and maintenance program, which ensures that the older vehicles also comply with the emerging vehicle standards. In the case of Patna, given the fraction of the in-use fleet under 15 years is very small (at less than 5%), banning this fraction of vehicles is not beneficial in the long-run compared to measures like changes in vehicle and fuel standards and reducing the usage of private vehicles and favoring public transport usage.

The average odometer reading in **Table 2** is consistent with typical usage rates. For example, motorcycles travelling for one hour/day at average speeds of 20-25 kmph will cover 6000-7500 km in a year. Similarly, cars and SUVs travelling 2 hours/day at average speeds of 15-30 kmph will cover 9000-18,000 km/year (assuming 300 operating days). These typical rates are useful when no data is available or the option to conduct surveys is not available.

Distribution of the vehicle usage numbers is presented in **Table 3**. On average

a) Diesel cars and diesel SUVs are used more than their petrol counterparts, often in the form of taxis
b) SUVs are 50% more used than cars
c) Large standard deviation and higher 95th percentile values in the VKT's of cars and SUVs represent the variants used as taxis
d) Similar variation is not apparent in the VKT's of motorcycles because these are mostly used for private transport. The larger VKT's represent delivery service vehicles which tend to travel at least double the number of km a day compared to personal trips
e) Like cars and SUVs, diesel autos and tempos are most preferred to support paratransit and freight movement needs.

The reported fuel economy (FE) numbers in **Table 4** align with typical trends, such as older vehicles being less efficient. On average, vehicles manufactured after 2010 show a 10% improvement compared to those produced between 2001 and 2010. Compared to the VKT numbers, the variation in FE is notably smaller. While VKT values often exhibit significant fluctuations, because of the use cases (such as personal vs taxi), the standard deviation of FE numbers tends to remain relatively stable, accounting for approximately 25% of the average values. This consistency highlights less variability in fuel efficiency across the dataset compared to the broader range observed in VKT metrics.

FE reported by manufacturers is often higher than the values experienced by drivers/owners in real-world conditions. This discrepancy arises due to several factors. Manufacturer-reported figures are based on standardized laboratory tests conducted under ideal conditions, often on a chassis dynamometer or on a racecourse with minimum load conditions and least obstacles on the road. Whereas a real-world scenario involves (a) varying road conditions such as uneven surfaces, potholes, and traffic congestion (b) driver behavior, including aggressive acceleration, frequent braking, and inconsistent speeds (c) stop-and-go nature of urban driving, characterized by frequent stops at signals or in traffic compared to the sustained speeds of highway driving (d) varying vehicle load conditions, as everyday use often involves additional weight from passengers, cargo, or accessories. These factors collectively explain why real-world FE often falls short of manufacturer-reported figures.

5. Application of Patna's Survey Data

The survey results served as a critical input for establishing the emissions inventory baseline for the city of Patna. This baseline was then utilized to study the city's air quality through the integration of a chemical transport model and a meteorological model. In this section, we present a summary of the study to highlight the potential of a localized survey in capturing vehicle use characteristics. For details, (BSPCB 2019) documents all the methodologies utilized to replicate on-ground trends in $PM_{2.5}$ concentrations and use of the inventories for evaluating the city's air quality management options.

For road transport emissions, the survey results were integrated with data on total vehicle registrations, vehicle usage patterns, fuel sales, and a composite of emission factors to calculate total emissions for all criteria pollutants. Overlaying with the geospatial (GIS) databases like population density, urban-rural classification, density of roads as primary, arterial, and feeder, and density of commercial and industrial activities, the total emissions were further disaggregated into grids of 0.01° resolution. The use of these GIS proxies for spatial disaggregation of the calculated emissions is illustrated in open tools @ https://www.urbanemissions.info/tools, along with a library of resource material to replicate the procedures and examples of previous applications in cities across Asia and Africa (Guttikunda, Bilkis et al. 2012, Guttikunda and Jawahar 2012, Guttikunda and Kopakka 2013, Guttikunda, Goel et al. 2014, Guttikunda, Zlatev et al. 2024, Okure, Guttikunda et al. 2025). **Figure 8** presents a composite of total emissions from all the known sectors for the Patna airshed at the grid level.

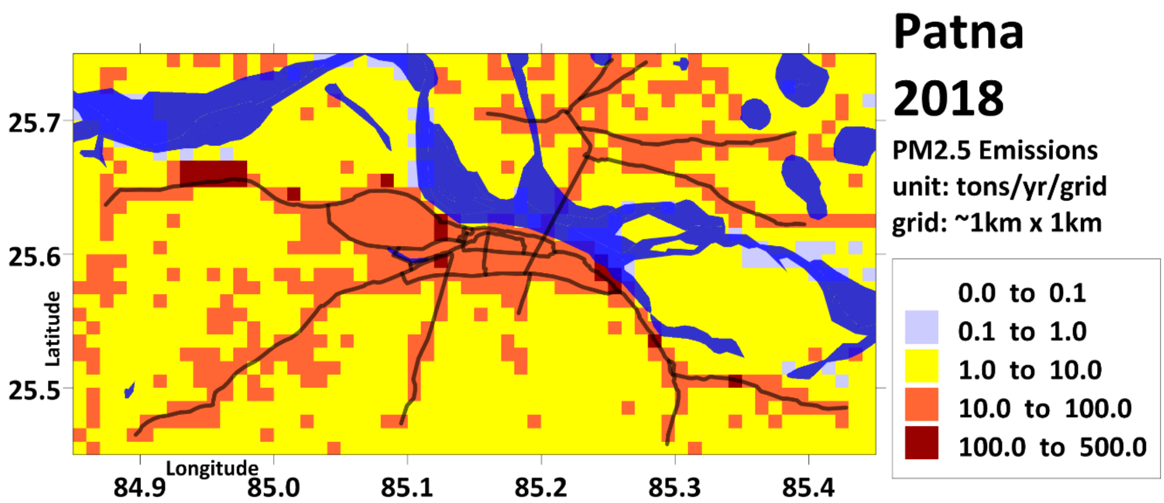


Figure 8: Illustration of total annual gridded $PM_{2.5}$ emissions for the Patna airshed in 2018

A gridded emission inventory is a critical input for assessing the spatial and temporal distribution of pollution using a chemical transport model. This approach not only enables the calculation of the overall pollution load within the airshed but also identifies pollution hotspots and estimates source contributions.

These insights are essential for informing policy dialogues and designing targeted mitigation strategies. The spatial patterns presented in **Figure 8** resemble a combination of the urban-rural classification and the road network. (Guttikunda and Jawahar 2014, BSPCB 2019) presents the methodological details of constructing this emissions map and an application of this inventory for pollution modeling, along with emission load details for the city of Patna based on the survey results in this case study.

The emissions and pollution modeling results were further used to assess a combination of the control measures under low-, medium- and high-compliance scenarios for future years till 2030 (**Figure 9**). In Patna, a 40% reduction in the annual average $PM_{2.5}$ concentrations is possible under the high compliance scenario – which is the clean air target for all the non-compliance cities under the national clean air programme of India (CPCB 2019, Ganguly, Selvaraj et al. 2020, India-PIB 2023, Guttikunda, Dammalapati et al. 2025). Most of the interventions planned for this what-if analysis focus on the transport sector. These include promoting electric vehicles for passenger transport, implementing programs to reduce private vehicle usage while increasing the share of public transportation, enhancing vehicle inspection and maintenance programs, and controlling road dust to minimize resuspension during vehicle movement. Vehicle combustion technology in India is already among the best available, and road dust management provides greater benefits for controlling PM_{10} pollution (the coarser particulate matter fraction) in urban areas (Yadav, Tripathi et al. 2022, Guttikunda, Dammalapati et al. 2025). The results demonstrate the use of a reliable emissions inventory, supported by input from the surveys conducted at the fuel stations in the city.

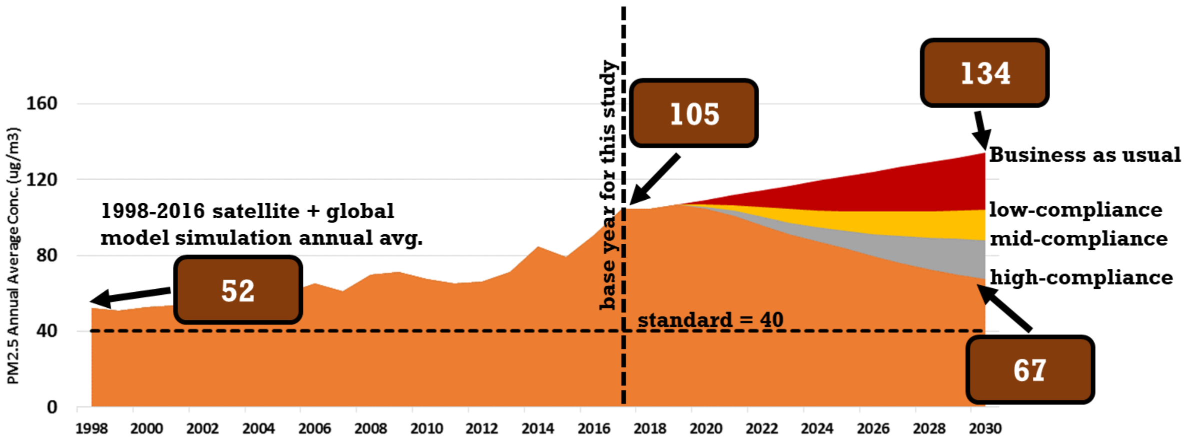


Figure 9: Illustration of total annual $PM_{2.5}$ concentrations between 1998 and 2020 from global reanalysis fields (van Donkelaar, Hammer et al. 2021) and projected to 2030 under business as usual scenario using the emissions inventory established under this study (BSPCB 2019); and three combinations of what-if scenarios based on the action plan proposed by the Bihar State Pollution Control

Applications in other cities

The FuSS framework was pioneered at the TRIP-Centre of the Indian Institute of Technology (New Delhi, India), with an application in Delhi and followed by surveys in Visakhapatnam, Rajkot, and Udaipur (Goel, Guttikunda et al. 2015, Goel, Mohan et al. 2016). After Patna, surveys were also conducted in Gaya and Muzaffarpur (also in Bihar) (BSPCB 2020) and Indore (Madhya Pradesh). A variation of the survey was used to analyze the in-use freight vehicle characteristics on Indian highways (Malik, Tiwari et al. 2019), in-use passenger vehicles in Mumbai (Raparthi and Phuleria 2022), and remote emission factor tests on select roads of Delhi and Gurugram (Narla, Bernard et al. 2024).

Uncertainty in FuSS applications

FuSS is a rapid assessment methodology designed for city-level applications to analyze the age distribution of vehicles and their usage patterns. While the methodology delivers quick results for understanding these metrics, it has some known limitations in its application. This survey is not a substitute for the large-scale surveys needed to comprehensively understand vehicle usage patterns for urban planning. This approach can complement broader studies by offering insights, serve as a valuable tool for assessing transport emissions and pollution, and provide a more localized representation of on-road vehicle conditions.

Here are some ways to identify and address the limitations in future studies

(a) Current applications were conducted at petrol stations, based on the assumption that vehicles in use would visit these stations over a period of one to ten days. However, the random selection of petrol stations introduces some inherent bias. Stations closer to the city center tend to reflect a different mix of vehicles compared to those located on the outskirts or farther from the city. Ideally, the survey should be conducted at all petrol stations to achieve a more comprehensive and representative understanding of the vehicle mix

(b) The study can be extended to other land-use types, such as malls, markets, schools, and large offices, to capture a more diverse mix of vehicle users and improve the representativeness of the findings. The need to coordinate data collection across multiple locations would further contribute to the complexity and logistical requirements of the study, in terms of time and cost

(c) The study can also be extended to highway junctions or city entry points to capture data from vehicles entering or exiting the city. However, the time available for conducting the questionnaire may be insufficient during toll collection, posing a potential limitation in these locations

(d) In the application for Patna, the sample size is limited to 1% of the vehicle fleet. This can be expanded to 5% or 10% of the registered fleet for a more comprehensive analysis, but such an extension would significantly increase the time and cost of the study. To optimize resources and ensure representativeness, the sample size should be pre-determined based on the specific locations of the sampling sites, accounting for the expected mix of vehicles in each area. This approach would help balance the trade-off between study accuracy and resource constraints

6. Way Forward

The FuSS framework explained and demonstrated in this paper is a rapid-form survey designed to collect key data points necessary for establishing the profile of in-use vehicles in a city. Unlike traditional surveys, which are large-scale, cover multiple land-use types, and often include household surveys, the FuSS framework is streamlined for efficiency. Traditional methods are typically expensive, time-consuming, and require significant personnel resources, whereas the FuSS framework can be implemented with minimal training for data collection and collation. And finally, the ODK app-based data archiving method facilitates tracking of survey samples by day and enables statistical analysis of the data within a timeframe of a day to a week, making it a cost-effective and practical alternative.

The framework can be replicated in places other than the fuel stations, which will result in a mixed set of results, but still useful for studying the in-use vehicle characteristics. For example:

(a) A survey can be conducted at the malls (either inside the malls or at the parking lot). Since this is a select set of users driving to the malls, the results can be used to study the travel behavior between income groups in the city and add to the overall pool of data from other surveys.

(b) A form-based survey at the schools, where the students can ask their parents to anonymously participate with information on the vehicle characteristics and personal trip patterns. In addition to increasing the data pool, the same can also be used to expand the origin-destination travel matrix of the city, with the schools as destinations.

When conducted en-masse, these surveys can provide a very rich dataset to not only evaluate the in-use vehicle characteristics but also help with the spatial disaggregation of the emissions to grids across the city airshed.

The vehicle fleets are constantly changing, and it would be ideal to conduct such rapid surveys every 3 to 5 years, to track the vehicle characteristics and travel behavior in the cities.

7. Data Availability and Resources

All the support files and presentations are available for open access at https://doi.org/10.5281/zenodo.11515540. This includes

(a) A copy of the survey form
(b) ODK app code which can be used to replicate or expand for similar applications
(c) A presentation showing the ODK screenshots on steps to enter data and save.

All the GIS layers necessary for gridding total emissions are pre-extracted and archived for open use at https://urbanemissions.info, along with example tools (under the tab "Resources") to conduct vehicle exhaust emission calculations, scenario analysis, and spatial allocation of total emissions to city grids. A version of tools is also uploaded to the public zenodo repository.

A copy of the vehicle stock numbers by age for India and its states, for the period covering 1993-2018 and applicable survival functions are published at https://doi.org/10.3390/su16156298 (Guttikunda 2024).

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