Studying non-tailpipe emissions from vehicles in *IIT Delhi* Campus and its contribution to total emissions

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Abstract
Non-tailpipe emissions (NPEs) from vehicles comprising of brake wear, tire wear, road abrasion, and resuspended dust, are emerging as a dominant yet understudied source of particulate matter (PM) in urban environments. While stringent regulations have reduced tailpipe emissions, NPEs remain unregulated and are projected to grow with increasing vehicular traffic and the adoption of heavier electric vehicles (EVs). This study quantifies the contribution of NPEs to ambient PM levels within the IIT Delhi campus, a microcosm of Delhi's urban traffic dynamics. Vehicle counts were conducted at a key junction over 5 days, categorizing traffic by type (2-wheelers, 4-wheelers, EVs, etc.) and time of day. Emission factors from literature were applied to estimate $PM_{2.5}$ and PM_{10} emissions from brake, tire, and road wear, as well as dust resuspension. Results reveal that NPEs exhibit strong temporal trends, peaking during rush hours, and are disproportionately influenced by heavier vehicles. Notably, EVs, despite zero tailpipe emissions, contribute significantly to NPEs due to their higher weight and tire-road interaction. The findings underscore the need for regulatory frameworks targeting non-exhaust emissions, especially in cities transitioning to EVs. Limitations include reliance on generalized emission factors and exclusion of local variables like road conditions. This study provides a methodological framework for urban NPE assessment and highlights gaps for future research in mitigating this growing pollution source.

1. Introduction

Urban air pollution remains a critical global challenge, with vehicular emissions accounting for a significant share of ambient particulate matter (PM) in cities. While extensive research and policy interventions have targeted tailpipe emissions—such as nitrogen oxides (NO_x) and exhaust PM—non-tailpipe emissions (NPEs) have received comparatively less attention despite their escalating contribution to urban PM loads. NPEs originate from mechanical wear processes, including brake abrasion, tire degradation, road surface wear, and the resuspension of settled dust due to vehicle movement. These emissions release fine ($PM_{2.5}$) and coarse (PM_{10}) particles, which are associated with severe health impacts, including respiratory diseases, cardiovascular conditions, and increased mortality rates.

Delhi, India, represents this problem, consistently ranking among the world's most polluted cities. While policies like Bharat Stage VI norms and EV adoption aim to curb tailpipe emissions, NPEs remain unaddressed. Compounding the issue, EVs—often heavier due to batteries—may exacerbate tire and road wear, offsetting some benefits of zero-exhaust emissions. Despite their significance, NPEs are poorly quantified in Indian cities, with limited localized studies to inform mitigation strategies.

This study addresses this gap by investigating NPEs within the IIT Delhi campus, a controlled yet representative urban micro-environment.

The objectives are threefold:

(1) To quantify traffic-derived NPEs using real-world vehicle counts and established emission factors.

(2) To analyze temporal and categorical trends in NPE contributions.

(3) To discuss implications for urban air quality management in the context of evolving vehicle fleets (1).

The campus offers an ideal study area, mirroring Delhi's diverse traffic mix (2-wheelers, cars, buses, EVs) and diurnal patterns. Vehicle counts were conducted at the Rajdhani Junction, a high-traffic node, using time-stratified sampling. Emission estimates were derived from methodologies like the USEPA AP-42 model (2)(3), accounting for variables such as vehicle weight and road silt loading. The study also evaluates the role of EVs in NPEs, challenging the perception of their "zero-emission" status. (4)

2. Methodology

Site characteristics

2.1. Study Area and Vehicle Data Collection
The study was conducted within the Indian Institute of Technology Delhi (IIT Delhi) campus, specifically focusing on the stretch of road between Gate 1 and Gate 6, covering an approximate distance of 2.5 kilometers. The selected observation point was the Rajdhani Junction, a key vehicular intersection on campus.

Vehicle counts were recorded over a four-day period during three distinct time windows each day: morning, afternoon, and evening. Each observation period lasted for 15 minutes. A manual counting method was employed using click counters, and vehicles were classified into the following categories:

2-Wheelers (2W)
Electric 2-Wheelers (E2W)
4-Wheelers (4W)
Electric 4-Wheelers (E4W)
Auto Rickshaws
E-Rickshaws
Heavy Vehicles (including buses, tempos, tractors, and trucks)

2. Estimation of Non-Tailpipe Emissions
Non-tailpipe emissions were categorized into four major sources: brake wear, tire wear, road surface wear, and road dust resuspension.
a. Total Emission Estimation
To estimate total emissions from non-tailpipe sources across the study segment, the following formula was used (5) –

$$E_i = \sum_{j=1}^{n} V_{ij} \cdot EF_{jk} \cdot L_i$$

Where:

E_i is the total emission (in grams) for the road segment i
V_{ij} is the number of vehicles of type j on road segment i
EF_{jk} is the emission factor (g/km/vehicle) for vehicle type j and emission type k (brake, tire, road wear, or resuspension)
L_i is the length of the road segment i

The emission factors were taken from literature sources, such as the work by Timmers and Achten (2016)(4), and supplemented by other peer-reviewed publications.
b. Emission Estimation from Dust Resuspension
The emission factor for particulate matter (PM_{10} and $PM_{2.5}$) due to resuspended road dust was calculated using the USEPA AP-42 (2011) formula (3):

$$E_f = K \cdot sL^{0.91} \cdot W^{1.02} \cdot \left(1 - \frac{P}{4N}\right)$$

Where:

E_f is the emission factor (g/VKT)
K is the particle size multiplier (PM_{10} or $PM_{2.5}$)
sL is the road surface silt loading (g/m^2)
W is the average vehicle weight (tons)
P is the number of wet days in a year
N is the number of days in the year (365)

Standard values were used for K, sL, W, and P, based on regional data and EPA recommendations due to the unavailability of hyper-local measurements.

3. Data Analysis and Visualization
Emission estimates and vehicle count data were processed and visualized using Origin software. Plots were generated to analyze:

- Temporal variations in vehicle traffic across morning, afternoon, and evening sessions
- Corresponding variations in PM emissions
- Category-wise emissions to determine the dominant non-tailpipe contributors

4. Assumptions and Limitations

- Uniform travel distance ($\approx$ 2.5 km) was assumed for all vehicles. In practice, actual distances traveled within the campus may vary significantly depending on the route and purpose of travel, leading to potential underestimation or overestimation of emissions for certain vehicle types.
- Emission factors were generalized and may not reflect local vehicle fleet characteristics (e.g., age, driving behavior). These factors were derived from literature or national averages and may not account for IIT Delhi-specific conditions like vehicle maintenance levels, stop-and-go traffic, or road gradients.
- Vehicle speed and real-time weather or road surface conditions were not accounted for. Factors such as humidity, rainfall, wind, and road dust moisture content have a direct impact on the level of road dust resuspension and wear emissions, and their exclusion introduces uncertainty in the emission estimates.

Despite these limitations, the methodology provides a practical and scalable approach to estimating non-tailpipe vehicular emissions in urban and semi-urban settings. It can be refined with local calibration and expanded with real-time environmental data for increased accuracy.

3. Calculations

Emission Factors

The emission factors for the different categories of vehicles, as presented in Table 1, are taken from the UK Department for Transport report of 2023 (6). For resuspension EFs, we have used the USEPA AP-42 (2011) (3) formula and data from Singh et al., 2020 (5).

Table 1 Non-exhaust PM_{10} and $PM_{2.5}$ emission factors for different vehicle types (in mg/km)

Vehicle Type	Tyre	Brake	Road
PM_{10}			
2W	4.7	3.2	2.5
3W	6.0	5.3	3.3
Car	7.3	7.3	4.2
LCV	8.5	8.5	5.2
Bus	15.0	15.0	9.1
HCV	20.0	20.0	10.2
$PM_{2.5}$			
2W	2.3	1.6	1.3
3W	3.0	2.6	1.7
Car	3.6	3.6	2.1
LCV	4.2	4.2	2.6
Bus	7.5	7.5	4.6
HCV	10.0	10.0	5.1

Vehicle Count Data

The vehicle count data recorded by us for traffic on the IIT-D main road is presented in Table 2. Please note that the data for the morning and afternoon of April 17th, as well as for the morning of April 21st, are missing due to unforeseen circumstances that led to the omission of these readings.

Calculating PM

Using the formulae mentioned above, the calculated emission data is recorded in Table 3. Please note that the units of these numbers is mg.

Inferences & Findings

Temporal trends in vehicle count

Vehicle counts were taken at three times - morning, afternoon and evening. It was observed that there were fewer vehicles in the evening (non-peak hours), reducing the emissions at night. The morning and afternoon sessions had higher vehicle counts, probably due to office / college commute times, causing higher emissions.

Category-wise vehicle contribution

On 18 April, we observe higher vehicle counts during the afternoon session and yet lower emissions, compared to the morning session. This observation leads to the inference that not all vehicle categories contribute equally to emissions. Coming back to the example, we see lower counts of 4 wheelers and higher 2 wheelers in the afternoon session, implying that 4 wheelers contribute more to emissions than 2 wheelers.

Date & Time	4-Wheelers	Electric 4-Wheelers	2-Wheelers	Electric 2-Wheelers	Auto	E Auto	Others
4/17/2025 9:35 PM	27	0	54	0	14	12	0
4/18/2025 10:00 AM	35	1	33	7	7	22	0
4/18/2025 4:10 PM	27	0	43	13	14	13	0
4/18/2025 10:50 PM	28	0	27	15	6	2	0
4/19/2025 10:15 AM	80	0	49	5	2	39	5
4/19/2025 5:30 PM	42	1	67	13	16	11	2
4/19/2025 10:00 PM	31	0	38	11	7	17	1
4/20/2025 11:23 AM	45	2	29	3	5	17	3
4/20/2025 4:30 PM	41	2	63	17	20	13	1
4/20/2025 9:16 PM	32	0	36	11	8	4	0
4/21/2025 4:41 PM	33	0	46	10	19	11	0
4/21/2025 9:50 PM	16	1	46	7	5	3	0

Table 2 Vehicle Count Data by Type and Time of Day (April 17-21, 2025)

Date & Time	Tyre_PM10	Tyre_PM25	Brake_PM10	Brake_PM25	Road_PM10	Road_PM25	Resusp_PM10	Resusp_PM25
4/17/2025 9:35 PM	1517.25	748.5	1269.25	628	835.5	427.75	22280.06422	5390.338118
4/18/2025 10:00 AM	1562	771.5	1361.25	672.5	867.25	442.25	468642.2196	113381.1822
4/18/2025 4:10 PM	1555.75	767.5	1298.5	642.5	856.25	438.5	547757.0509	132521.8672
4/18/2025 10:50 PM	1124.5	553.5	953	472	622.5	317.5	313230.2741	75781.51793
4/19/2025 10:15 AM	2709.5	1338	2435.25	1202.5	1515.75	769.75	53307.00717	12896.85657
4/19/2025 5:30 PM	2129.75	1049.5	1782.5	882.5	1174.25	600.5	32708.94775	7913.455102
4/19/2025 10:00 PM	1501.5	740.75	1275.75	631	829.75	424	23784.33264	5754.274026
4/20/2025 11:23 AM	1563.75	772	1405.25	694	875	444.25	30988.47706	7497.212192
4/20/2025 4:30 PM	2219.75	1094.5	1862	921.5	1223.75	626	33705.811	8154.631694
4/20/2025 9:16 PM	1316.25	648.25	1119	554	728.75	371.75	22202.19331	5371.498382
4/21/2025 4:41 PM	1710.25	844	1447.75	716	944	482.75	26301.79772	6363.338158
4/21/2025 9:50 PM	1053	517.75	840.25	417	575.75	295.5	13842.15031	3348.907333

Table 3 PM Concentration Data for Various Sources (Tyre, Brake, Road, Resuspension) on IIT-D Main Road

Electric vehicles still produce non tailpipe emissions

EVs, despite producing zero tailpipe emissions, still produce non tailpipe emissions and hence are not completely emission free. It is also to be noted that since 4 wheeler EVs are heavier than 4 wheeler combustion based cars, the former likely produces more emissions than the latter does.

Brake wear and tire wear emissions

It was observed that brake wear contributed more to the $PM_{2.5}$ concentration, meanwhile tire wear contributed more to PM_{10} concentrations. This is likely due to brake wear producing mostly fine particles such as metallic dust and carbon, compared to tire wear producing coarser rubber particles.

Conclusions

In this study, we took the data of different categories of vehicles passing through IIT Delhi at 3 different equally spaced sessions per day. From this, we estimated the total emissions from brake wear, tire wear, road wear and resuspension, using emission factors. We observed that heavier vehicles contributed more significantly to emissions, and also that road dust resuspension was the dominant source of non-tailpipe PM emissions.

Future Work

How does regenerative braking reduces brake wear?

Brake wear particles are generated when traditional (mechanical) brakes apply friction to the wheels to slow down a vehicle. Non-tailpipe emissions, particularly brake wear particles, are generated when traditional (mechanical) brakes apply friction to the wheels to slow down a vehicle. This friction physically wears down brake pads and rotors, producing particulate matter (PM), especially PM_{10} and $PM_{2.5}$, which are harmful to both human health and the environment.

Regenerative braking works differently: in regenerative braking, when a vehicle slows down, the electric motor that normally drives the wheels switches roles and acts as a generator. Instead of using friction brakes, the motor resists the wheel's rotation and converts the vehicle's kinetic energy into electrical energy, which is sent back to recharge the battery. Because slowing down happens mostly through the motor and not mechanical friction, the use of physical brake pads is greatly reduced.

Thus, regenerative braking reduces non-tailpipe emissions by reducing brake pad usage. Since the vehicle slows using the motor, the brake pads are used less frequently and with less force, meaning less brake material is worn away and released into the air.

It also lowers brake pad temperature. Traditional braking generates heat, which can cause more fine particles to become airborne. Regenerative braking is an electric process, minimizing the heating and associated fine particle generation.

Moreover, regenerative braking increases brake system life. Regenerative braking not only reduces emissions but also extends the lifespan of brake pads and rotors, leading to fewer replacements and less production-related emissions.

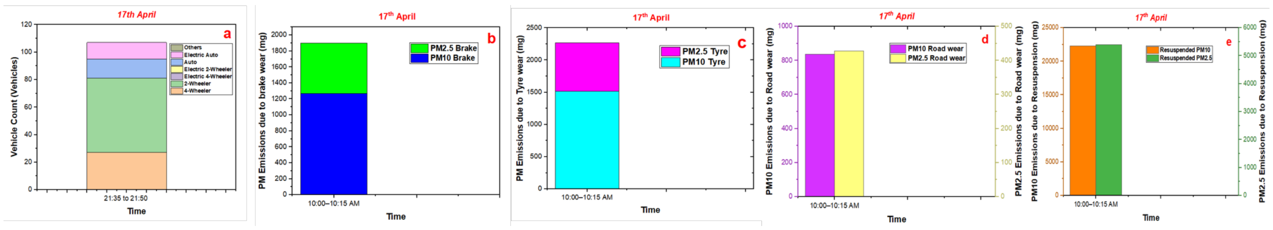

Figure 1 17th April a-Hourly vehicle count distribution on 17th April 2025 ,b-Estimated PM emissions due to brake wear,c-Estimated PM emissions due to tyre wear,d-Estimated PM emissions due to road wear,e-Estimated PM emissions due to dust resuspension.
Plots made in Origin software

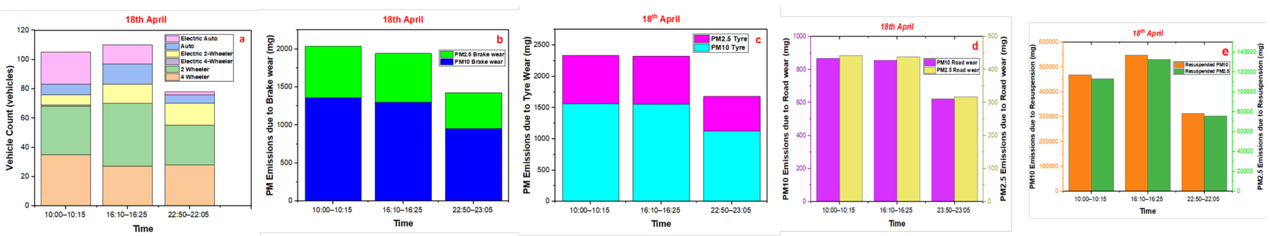

Figure 2 18th April a-Hourly vehicle count distribution on 18th April 2025 Peak traffic is observed in the morning and afternoon sessions, while evening traffic shows a noticeable dip.,b-Estimated PM emissions due to brake wear,c-Estimated PM emissions due to tyre wear,d-Estimated PM emissions due to road wear,e-Estimated PM emissions due to dust resuspension.
Plots made in Origin software

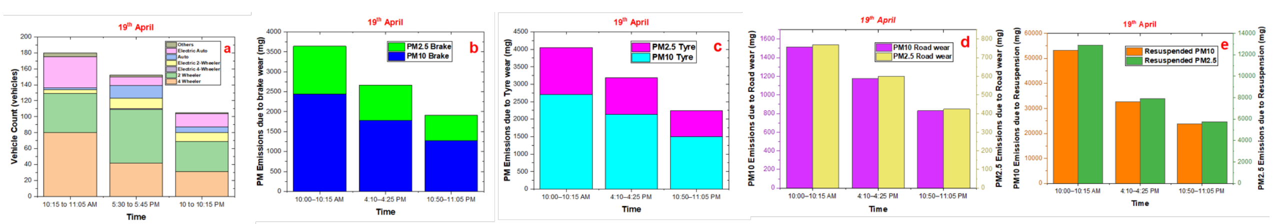

Figure 3 19th April a-Hourly vehicle count distribution on 19th April 2025 Peak traffic is observed in the morning and afternoon sessions, while evening traffic shows a noticeable dip.,b-Estimated PM emissions due to brake wear,c-Estimated PM emissions due to tyre wear,d-Estimated PM emissions due to road wear,e-Estimated PM emissions due to dust resuspension.
Plots made in Origin software

Super Emitters – what are they?

Superemitters are a small fraction of vehicles that are responsible for a disproportionately large amount of net vehicular emissions. Traditionally, they are associated with large amounts of exhaust emissions such as Nitrogen Oxides (NO_x), Carbon Monoxide (CO) and Particulate Matter (PM), but they are also increasingly relevant when considering non-tailpipe emissions as well. As vehicle engines become cleaner with stricter emissions standards and electric vehicles' rise, non-tailpipe sources are becoming dominant contributors to urban particulate pollution. Superemitters could be older, poorly maintained, heavily used, or very heavy vehicles that generate an excessive amount of non-tailpipe emissions, contributing disproportionately to localized air quality issues and public health risks. Examples of such vehicles are trucks, buses, etc.

Future Research & Open Questions

The main aim of future research would be to tackle the limitations we had in this study. Some of these could be –

- A more accurate measure of the distance traveled by vehicles could be obtained by noting down the purpose of visit for each vehicle, allowing for a better estimate
- Inclusion of local emission factors (based on in-situ measurements) may improve the accuracy of emission estimates

Some open questions for future research are –

- How does real-time meteorological variation (e.g., wind speed, humidity, rainfall) affect the rate of non-tailpipe emissions?
- What is the role of road surface materials and maintenance practices in influencing non-tailpipe emissions?
- What is the impact of non-tailpipe emissions on indoor air quality in adjacent buildings or classrooms near high-traffic roads?

Credit authorship contribution statement

Ayaan Shaikh: Term paper framework, Writing - original draft, write-up-Abstract and Introduction section, Methodology and Results section. Plotting all the plots, results tabulation, software tools (Python, Origin), Inferences, on-site data collection,editing, reviewing, reference section (using Mendeley and bib file of Latex).
Shayan Majumdar: Project ideation, collected data on-site, tabulation and calculations regarding emission factors and PM, creation of tables, writeup on calculations and results, editing/formatting.
Arnav Jain: Write up for inferences & findings section, conclusions section, future research & open questions section, collected on-site data for vehicle counts, tabulation of data, and editing the term paper.
Himesh Rustagi: Write up for super emitters, study area and vehicle data collection, collected on-site data for vehicle counts, tabulation of data.
Saatvik Kumar: Write up for conclusions, limitations and how regenerative braking reduces brake wear, collected on-site data.

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