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Development of a GIS-Based Approach for Spatial Disaggregation of Emissions from Road Traffic

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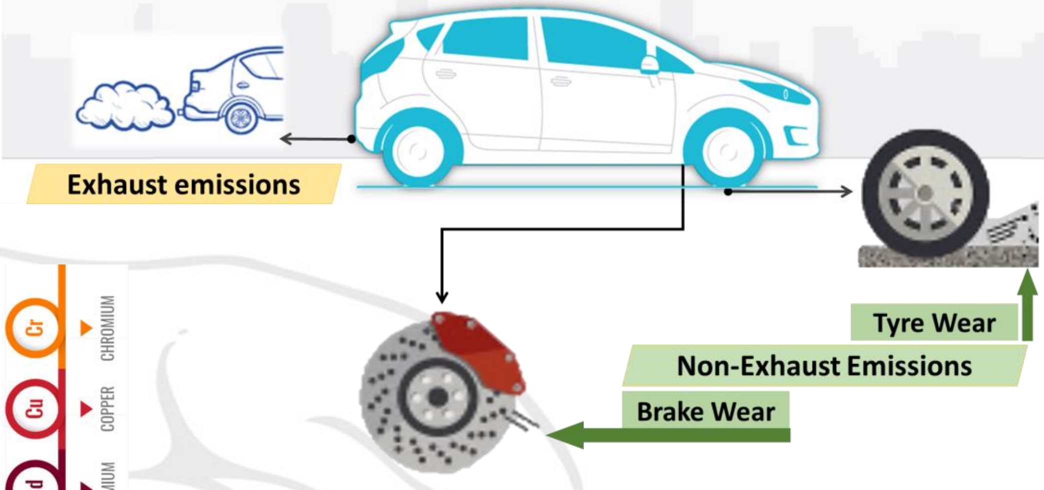
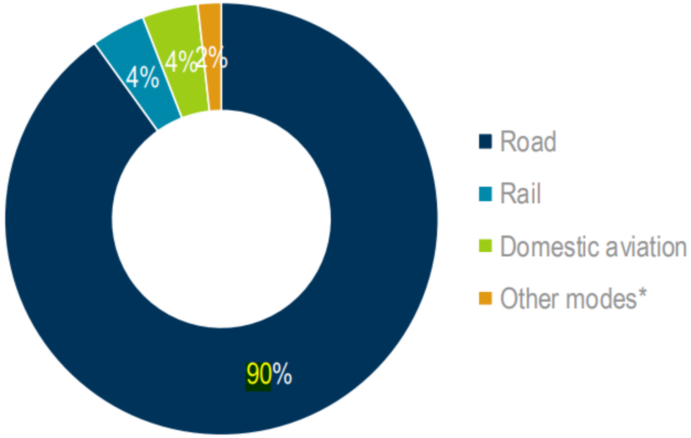
Introduction

- The rapid increase in urbanisation and motorisation has led to a significant rise in emissions from road traffic.
- **Vehicle exhaust emissions** play a central role in **urban air quality management** at the urban scale (Goel et al. 2015).

- **Emissions from road transport** greatly impact ambient air quality, leading to health risks for humans. These emissions contain **heavy metals** which poses significant health risks due to their **inherent toxicity** and tendency to accumulate within the human body (Suvarapu & Baek, 2017).



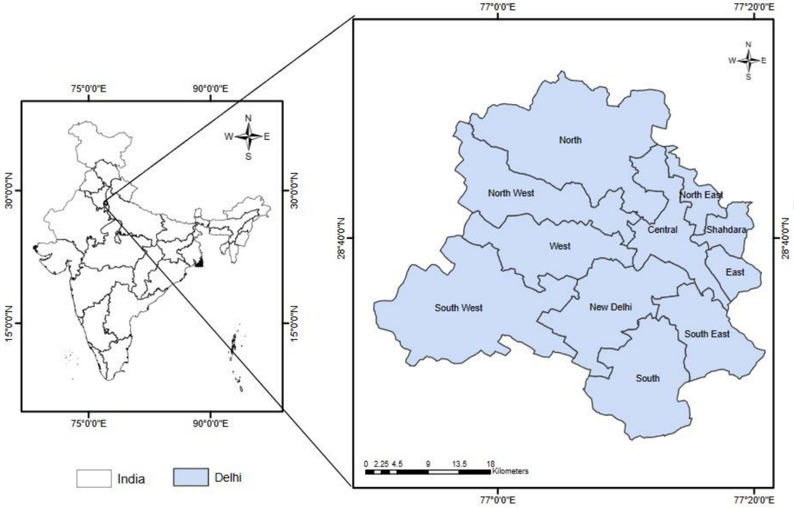


Source: Energy Policy Review, IEA, 2020

The **Indian transport sector** is responsible for **13.5 per cent** of India's energy-related **CO_2 emissions**, with road transport accounting for **90 per cent** of the sector's total final energy consumption, followed by rail and domestic aviation (both at 5 per cent) (IEA, 2020).

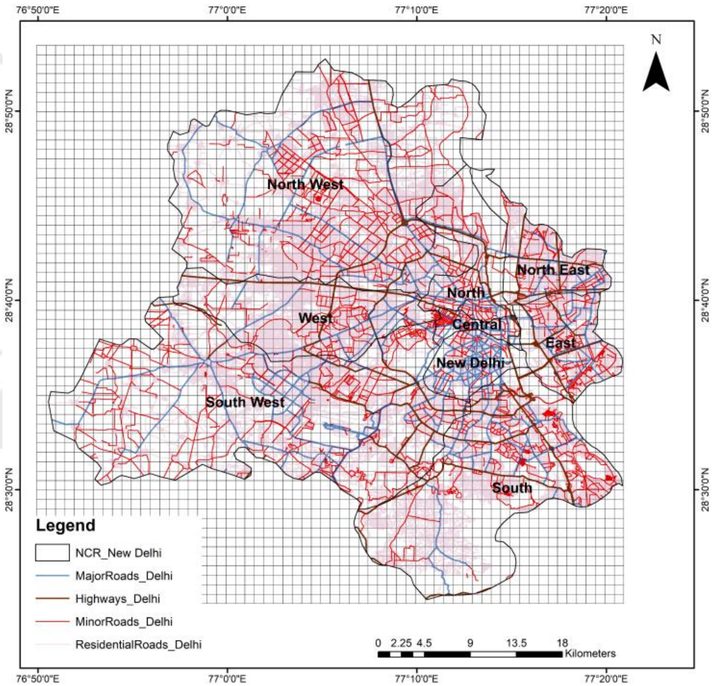
Heavy Metals (HM) emissions from road transport, such as Chromium (Cr), Nickel (Ni), Lead (Pb), Arsenic (As), and Cadmium (Cd), are emitted not only from the **exhaust** but also from **non-exhaust** sources like tyre-wear and brake wear (Kumari et al. 2013).

Study Area



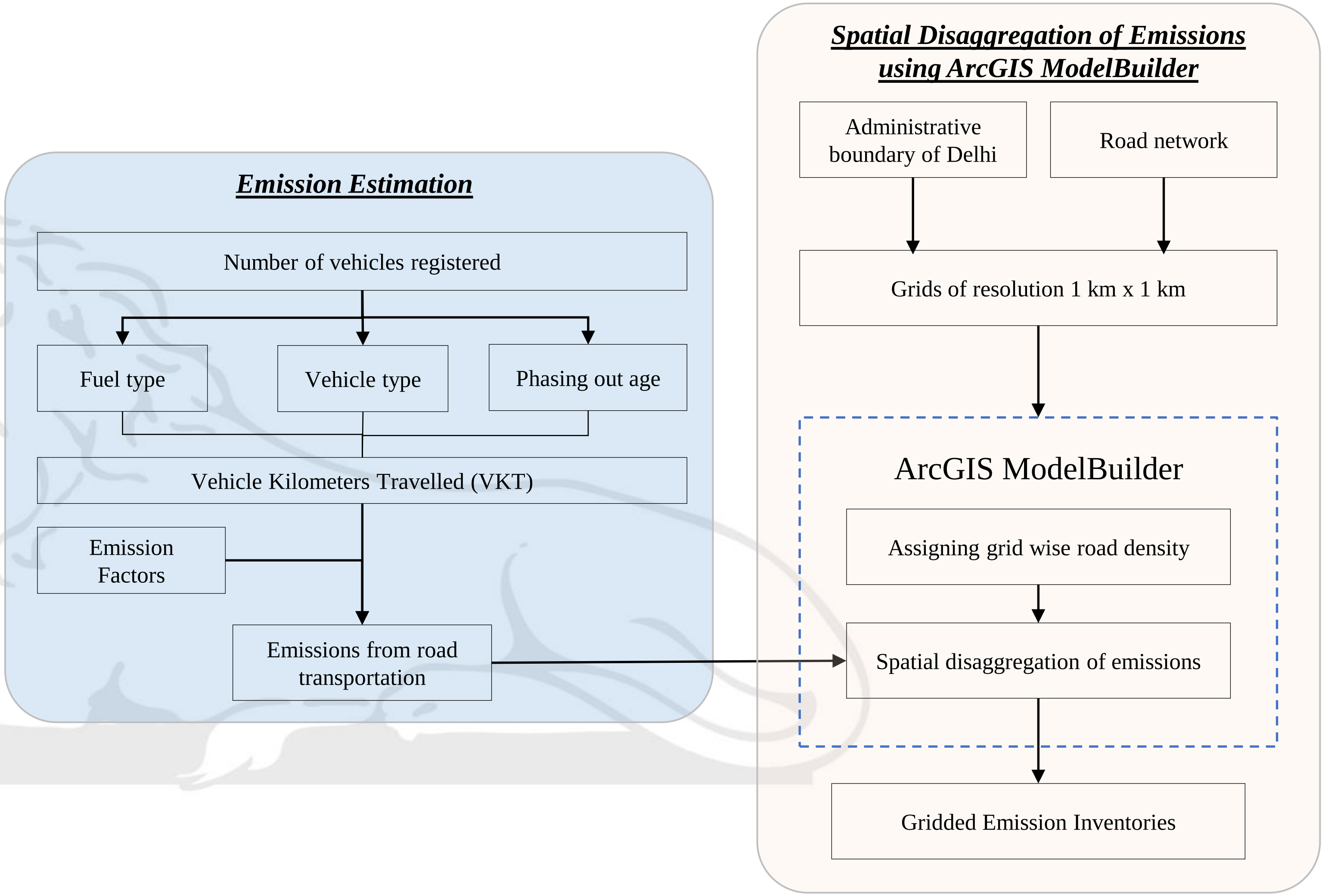
Features of the study area	
Area	1484 km^2
Coordinates	28.7041° N, 77.1025° E, lies in northern part of India.
Road length	22065.821 km (Approx.)

- The **road network** is divided into four categories: Highways (State/National Highways), Major roads (intrastate and interstate travel), Minor roads (linking to major roads), and Residential roads (primarily used for local transit).
- The emissions per grid are estimated according to the vehicular count, vehicle kilometer travelled, and emission factor and then gridded using a **Geographic Information System (GIS).**
- Grid-based **road density** (defined as the number of km of road per grid) was used as a proxy to distribute the emissions.



Methodology

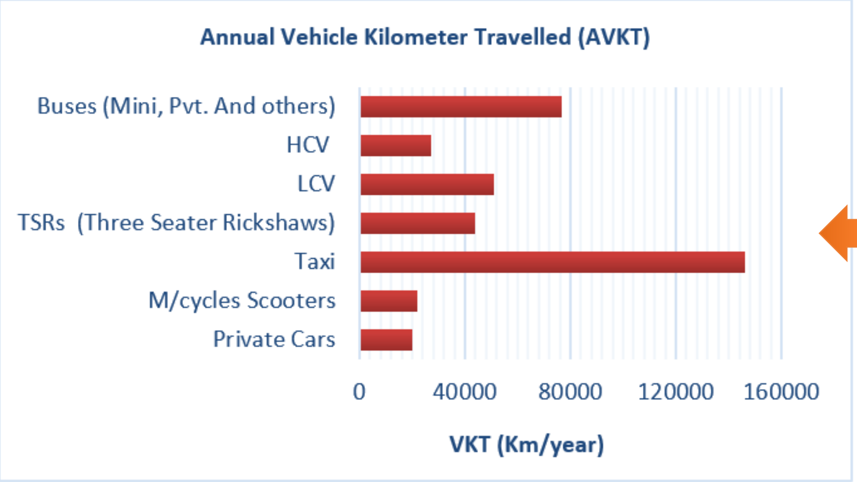
- ✓ **In this study, the total emissions are distributed into grids of 1 km^2 over Delhi.**
  - The **gridded road density**, defined as the total road length in a grid, is taken as the allocation factor to spatially disaggregate the emissions.
  - A **grid** with a high value of road density indicates a correspondingly high level of emissions.
  - It is assumed that **emissions** from vehicular sources are directly proportional to **road density**.



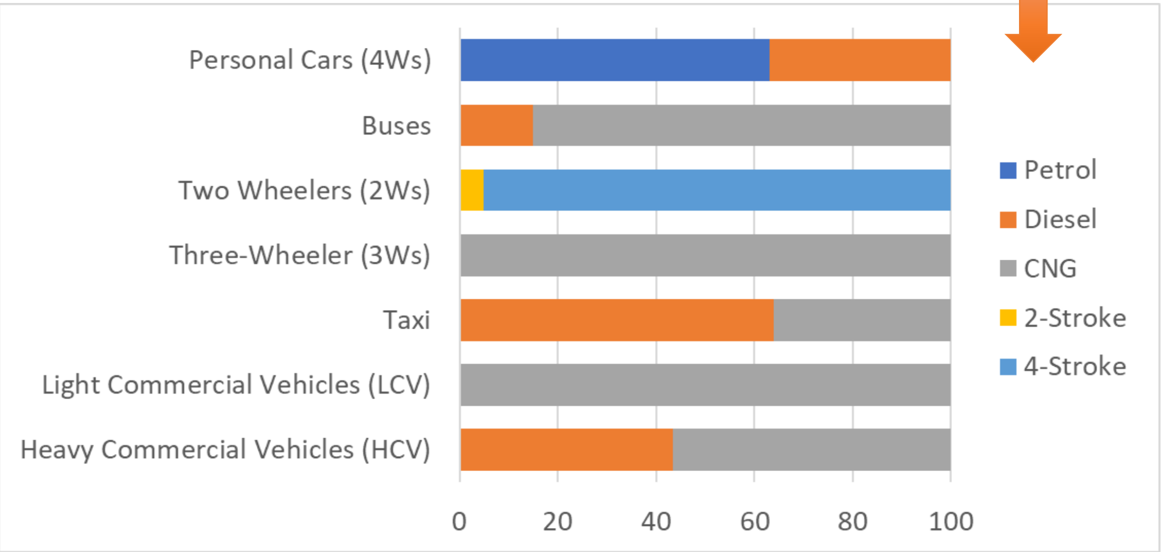
Methodology

- In this study, the total **number of vehicles** is classified into seven categories:

Vehicle categories	Grouped based on
Personal Cars (4Ws)	✓ Fuel type (Diesel/CNG/Petrol) ✓ Technology type (Bharat Stage-I, II, III, IV) ✓ Vehicle age (Goel & Guttikunda, 2015).
Two Wheelers (2Ws)	
Taxis	
Three-Wheeler (3Ws)	
Light Commercial Vehicles (LCV)	
Heavy Commercial Vehicles (HCV)	
Buses	



- The **on-road vehicle fleet** has been computed using the categories from the "System of Air Quality and Weather Forecasting and Research (SAFAR)" (Gufran & Sahu, 2018) and (Goel & Guttikunda, 2015). The percentage distribution of vehicles according to fuel type is given below:



- **Annual Vehicle Kilometres Travelled (AVKT)** is a measure of the total distance in kilometres travelled by vehicles in a year. AVKT of different vehicle categories obtained through a survey (Gufran & Sahu, 2018).

Emission Calculation

Non-Exhaust Emission

- The present work adopted the "**bottom-up**" approach, which not only improves accuracy and reliability but also **minimize uncertainty**.
- The **non-exhaust emissions** from a variety of vehicle classifications can be calculated by multiplying the **algebraic sum of the vehicles with their respective annual vehicle kilometres travelled and the emission factor.** The equation for calculating non-exhaust emissions is as follows (Pulles et al., 2012).

$$\boldsymbol{E_t} = \sum (\boldsymbol{V_i} \times \boldsymbol{D_i}) \times \boldsymbol{E_{f,l\,km}}$$

$\boldsymbol{E_t}$ = Total Emissions.
$\boldsymbol{V_i}$ = Number of vehicles per category.
$\boldsymbol{D_i}$ = Distance travelled in a year per vehicle.
$\boldsymbol{E_{f,l\,km}}$ = Emission factor of metal, vehicle type per driven km.

Exhaust Emission

- The exhaust emissions of heavy metals is estimated using **Tier 1 method** from **EPA Emission Inventory Guidebook 2019.**
- The Tier 1 methodology uses **fuel** as the activity indicator, in combination with average **fuel-specific emission factors**.
- The **total annual fuel consumption** of the vehicle category and **emission of heavy metals** is calculated with the following equation:

$$FC_{i,f} = \sum_{j=1}^{7} \sum_{k=1}^{5} (N_{jk} \times AVKT_{jk} \times FCF_{jkf})$$

$$E_{HMs(ijk)} = EF_{HM(f)} \times FC_{(ijk)f}$$

FC_i = annual fuel consumption estimated in year 'i' (in kg).

N_{jk} = number of vehicles of category 'j' and falling in compliance class 'k'.

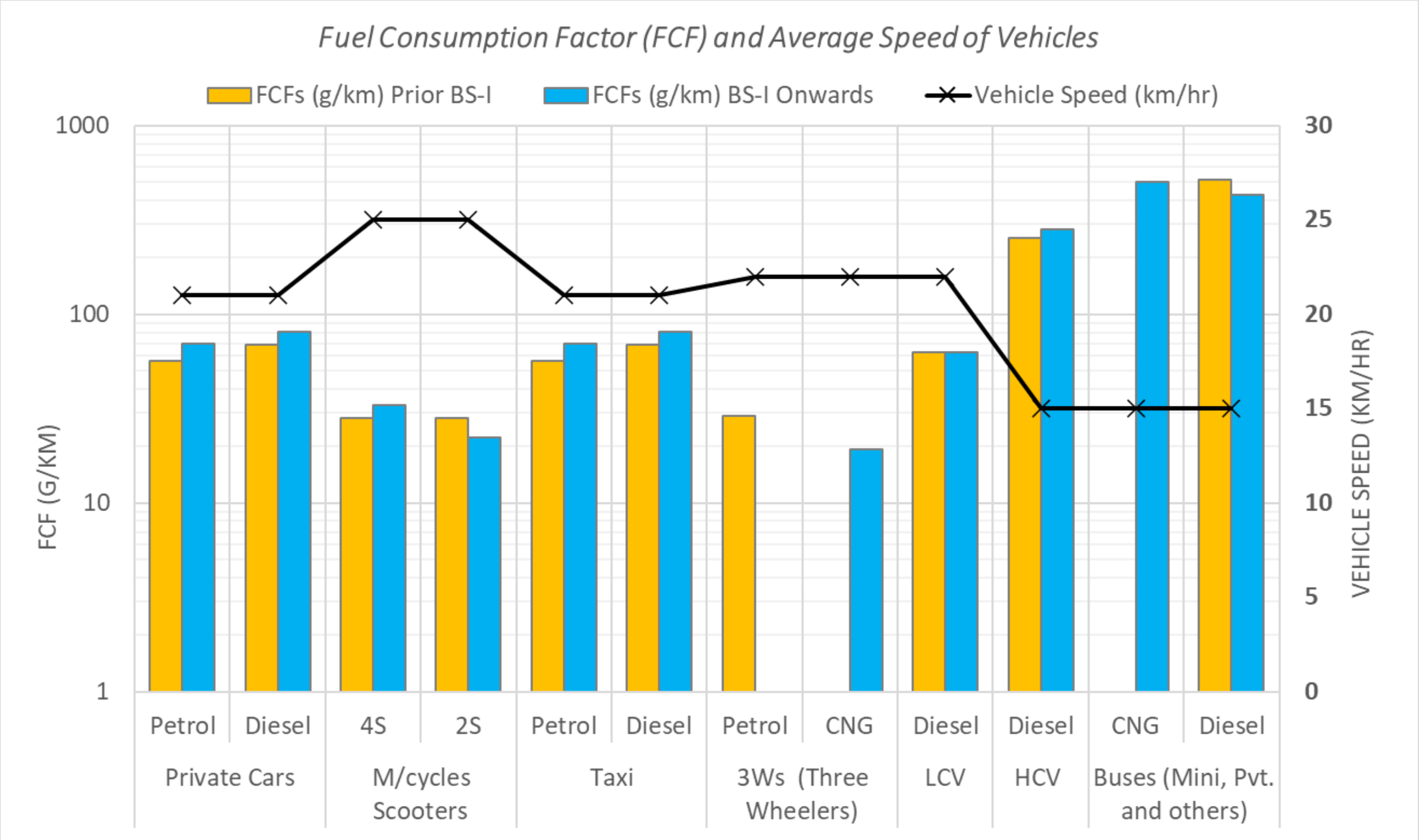
$AVKT_{jk}$ = average annual vehicle kilometer traveled (in km) for vehicle category 'j' and falling in compliance class 'k'.

FCF_{jkf} = Fuel consumption factor of vehicle category 'j' under compliance class 'k' for fuel type 'f' (g/km).

EF_{HMs} = Emission factor of corresponding heavy metals.; E_{HMs} = Emission of heavy metals except (g/year).

Fuel Consumption Factor (FCF) of different Vehicles Category-wise

- The fuel consumed by a vehicle is estimated using the **Fuel Consumption Factor**, which depends on the average speed of the respective vehicle.
- Mathematically, **FCF = *f* (average speed of the vehicle)**



Equation of FCF = *f* (V)	**Vehicle category**
$98.336 - 1.604V + 0.0106V^2$	CAR P
$118.489 - 2.084V + 0.014V^2$	CAR D
$0.0198V^2 - 2.506V + 137.42$	LCV
$1068.4\ V^{-0.4905}$	HCV
$1371.6\ V^{-0.4318}$	BUS D
$-0.00110\ V^2 + 0.2008\ V + 17.80$	2W 2S
$0.01890V^2 - 1.8740V + 67.90$	2W 4S

*V= average speed of the vehicle (km/hr)
Reference: COPERT Reference Manual

Emission factor

- ✓ An **emission factor** (EF) represents the measure of a **pollutant emanating** into the air due to the **activity associated with emission sources** (Gufran & Sahu, 2018).
- ✓ Kumari et al. (2013) provided **EFs** to calculate the **tyre wear and brake wear** emissions, as listed in **Table 1.**
- ✓ In the **exhaust emissions** estimation, two emission factors were employed: (i) **COPERT** (Ntziachristos, Leonidas and Samaras, 2000) (ii) **EEA Emission** Inventory Guidebook (Ntziachristos & Samaras, 2019) as shown in **Table 2.**
- ✓ **Table 3** presents the timeline of **Lead (Pb)** content based on technology type.

Table 1 Emission factor for estimating non-exhaust emissions (Kumari et al., 2013)

Vehicle categories	Non-Exhaust emissions	Heavy Metals Emission factors (µg/kg)						
		As	Cd	Cr	Ni	Pb	Cu	Zn
2W, 3W, Cars, Taxi, LCVs	Tyre Wear	0.054	0.18	18	2.6	49	470	118
	Brake Wear	0.035	0.044	0.22	0.28	1.6	--	--
Buses, HCVs	Tyre Wear	2.5	0.84	87	12	230	470	118
	Brake Wear	0.11	0.13	0.67	0.83	4.9	--	--
Reference		(Kummer et al., 2009)					(Johansson et al., 200	

Table 2 Emission factor for estimating non-exhaust emissions (in µg/kg).

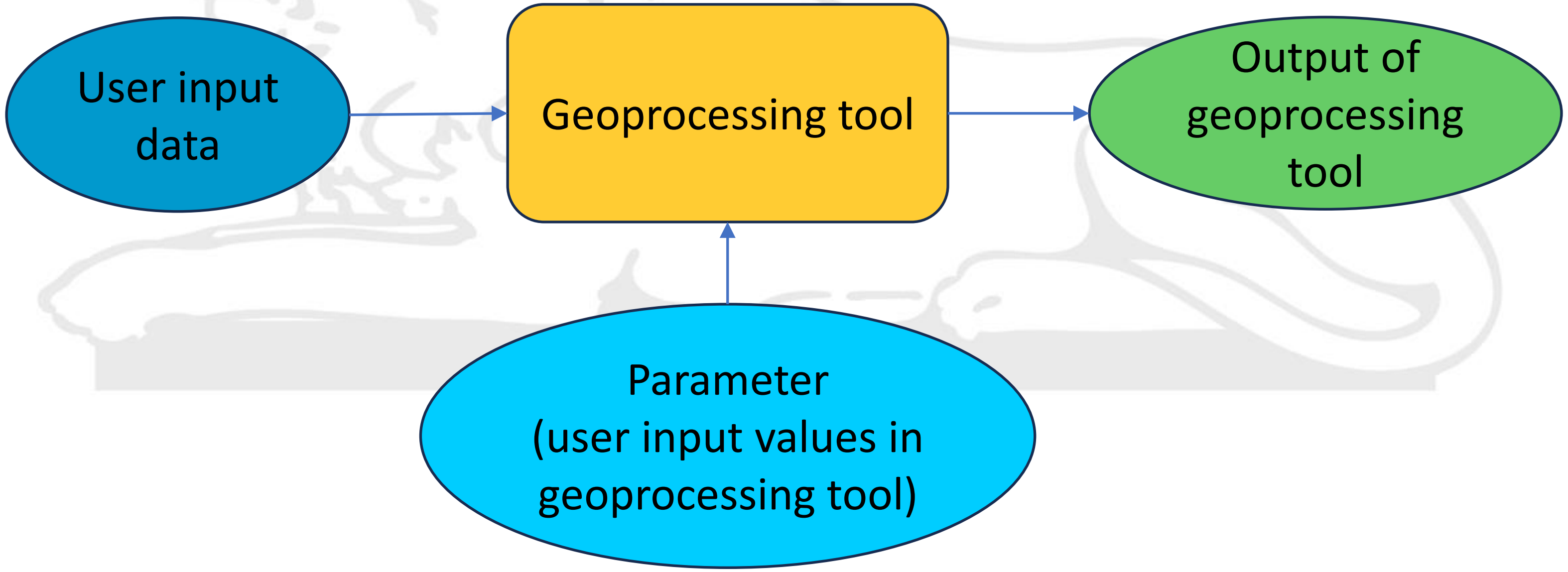
FUEL	As	Cd	Cr	Cu	Hg	Ni	Pb	Se	Zn	References
Diesel	–	10	50	1700	–	70	–	10	1000	(Ntziachristos, Leonidas and Samaras, 2000)
	0.1	0.05	8.5	5.7	5.3	0.2	0.5	0.1	18	(Ntziachristos & Samaras, 2019)
Petrol	–	10	50	1700	–	70	–	10	1000	(Ntziachristos, Leonidas and Samaras, 2000)
	0.3	0.2	6.3	4.5	8.7	2.3	1.6	0.2	33	(Ntziachristos & Samaras, 2019)

Table 3 Timeline of Lead (Pb) content based on compliance classes

Compliance classes	BS – I	BS – II	BS – III	BS – IV
Lead (Pb) content (g/kg)	0.017	0.017	0.007	0.007

ModelBuilder

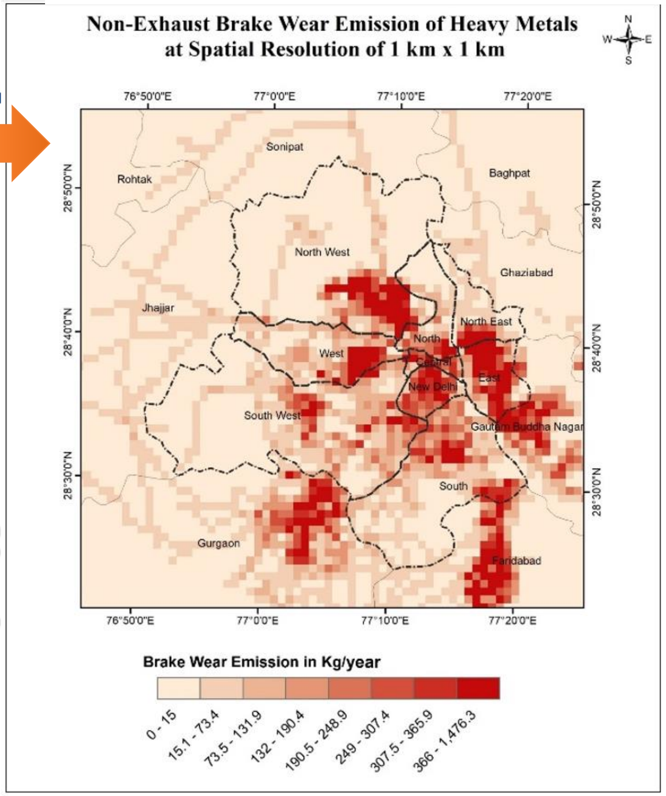
- ✓ ArcGIS *ModelBuilder* offers an excellent framework for linking tools and data to facilitate the spatial analysis and disaggregation of emissions.
- ✓ The input data required in this model are the total emission value to be distributed and the shapefiles of the administrative boundary and road network of any geographical region.
- ✓ The final output of the model is the spatially resolved emission inventory at any specified resolution based on the gridded road density.

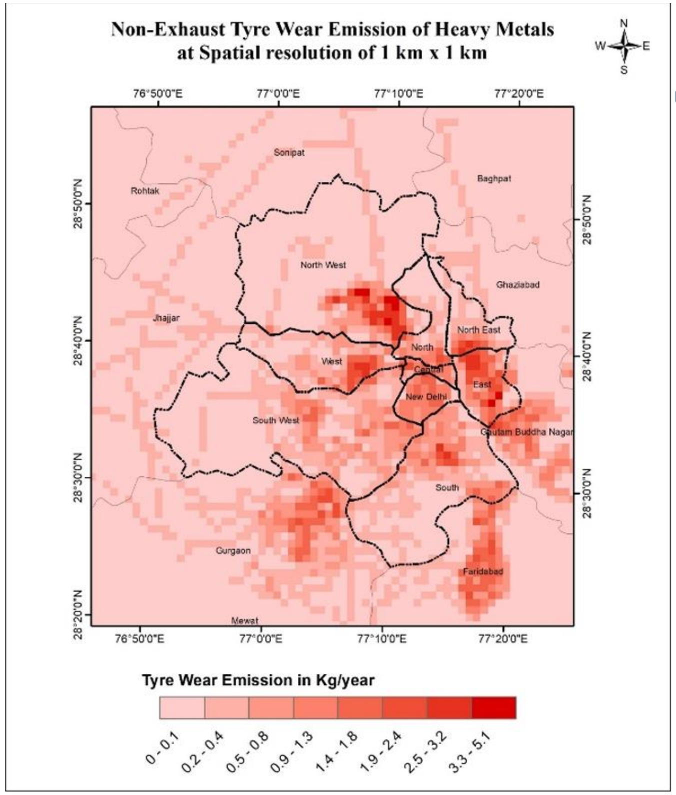


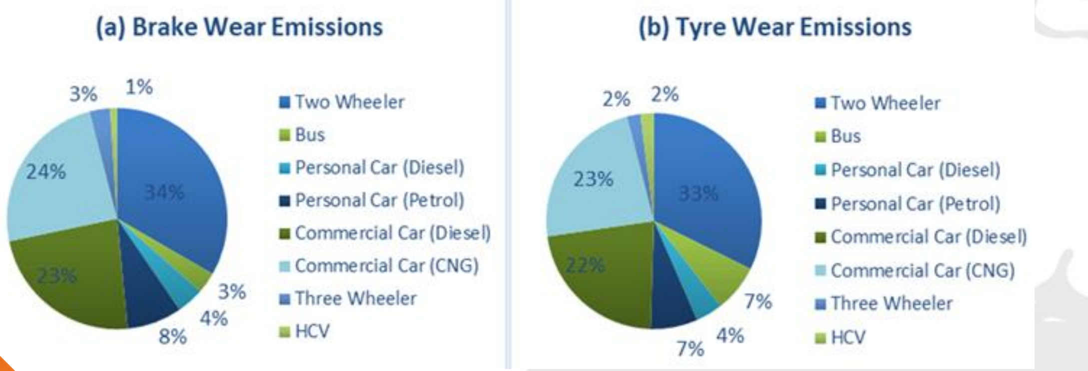
Results : Brake wear and tyre wear emissions

- In the **densely populated** city of Delhi, the overall **non-exhaust emissions** due to the wear of brakes and tyres amount to **122.23 Mg per year and 427.02 kg per year**, respectively
- The **highest brake emissions**, **36.57 Mg/year**, are found **in North West Delhi**, while the **lowest emissions** are **7.01 Mg/year**
- The **eastern part of Delhi exhibits higher** emissions of **27.13 Mg/year** compared to the **western part**, which has **21 Mg/year**
- The **central region has the highest tyre wear** emission of **127.50 Kg/year** and the **lowest emission** of **24.47 Kg/year**

Spatial distribution of emissions of heavy metal gridded at 1 km^2 resolution







Comparative share of vehicles to total non-exhaust emissions

- **Two-wheelers (2Ws) are significant contributors**, accounting for 33% and 34% from both tyre and brake wear emissions, respectively.

District wise emissions

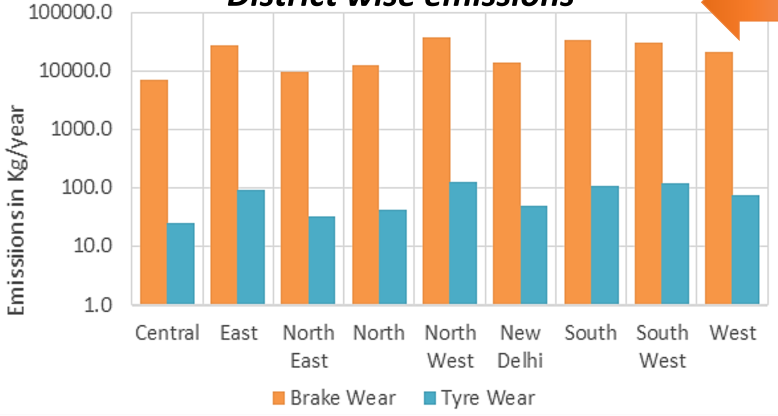


Figure 6 depicts that districts with larger areas (northwest and southwest) tend to have higher emissions than smaller districts.

- **The north and southwest** of Delhi have **higher tyre wear** emissions **than the rest** of the city

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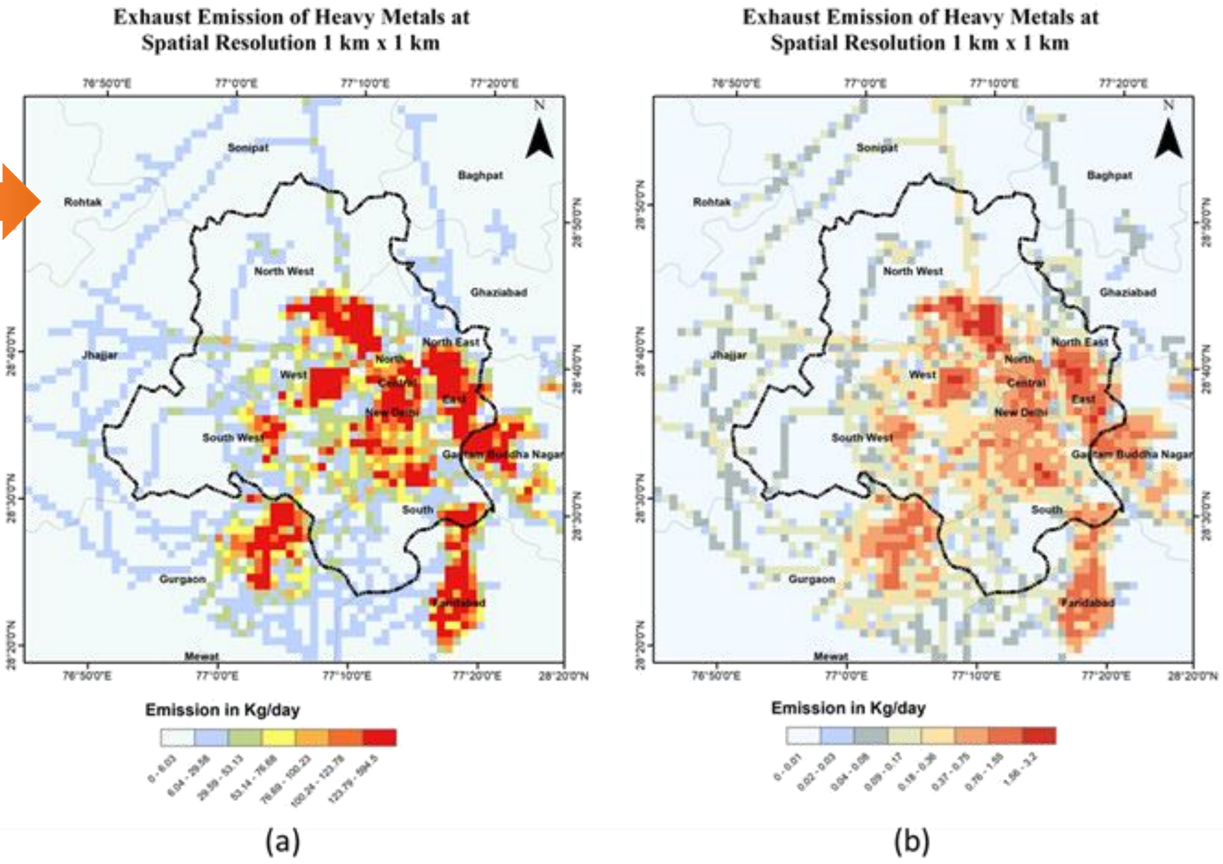
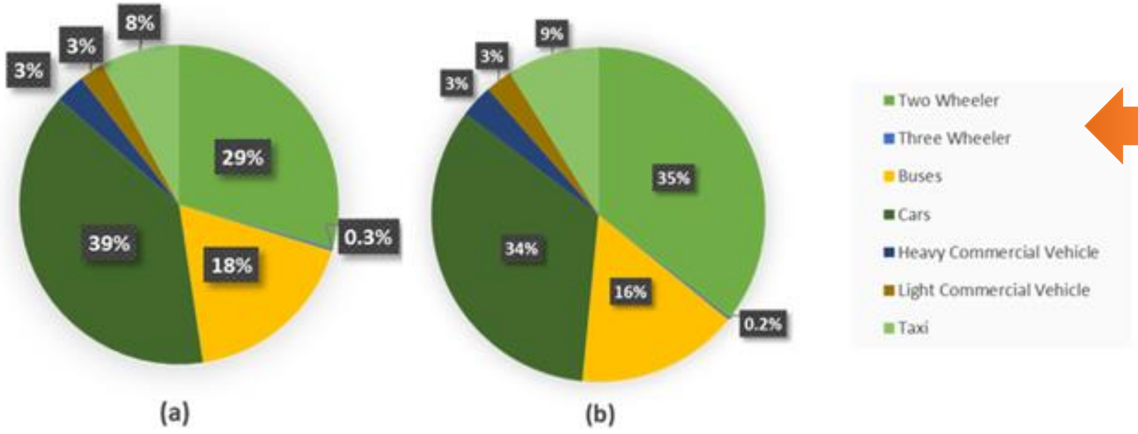
Results: Exhaust emission

- This study employed **two emission factors** to estimate heavy metal emissions from different vehicle types.
- Despite the uncertainties surrounding the total emissions, there is a **similar pattern** in the **contribution** of vehicles to the overall exhaust emissions.
- The methodology based on **COPERT III lacks** the ability to provide an **emission factor for lead** (Pb). The emission factor for **Lead** was derived from (CPCB, 2015) **based** on the **fuel type.**



Spatial distribution of exhaust emissions gridded at 1 km2 resolution based on (a) COPERT III (b) EEA Emission Inventory Guidebook 2019



- **Private cars and two-wheelers** were identified as the **most polluting** vehicle categories, followed by buses.
- It was found that **Copper (Cu~60%) and Zinc (~35 %)** were the **major** contributors to total emissions for 2018.

Conclusion

- A GIS-based **emission inventory** gridded at **1 km x 1 km** resolution was developed for Delhi. **Heavy metal emissions** from **road transport** sources, including **both exhaust and non-exhaust emissions** are estimated using a “bottom-up approach”.
- The study **integrates the methodology of emission models** (VAPI and COPERT) to **estimate the emission of heavy metals** from **on road vehicles** and the **develop a tool in *ModelBuilder*** in ArcGIS to **spatially disaggregate the emission** over the megacity of Delhi.
- The process of **disaggregating the emissions** involves the use of **different tools** in ArcGIS. A single model was developed in ArcGIS ***ModelBuilder*** with all required tools to distribute emission over a geographical region.
- It was discovered **that copper (71%) and lead (73%)** were the primary metals found in brake and tyre wear emissions, respectively.
- The **exhaust emissions** are accompanied with **uncertainties** due to the considerable variations in emission factor, **two emission factors** were considered for exhaust emission estimation. The **uncertainty in emission** parameters **do not affect the percentage share of emissions** from different vehicle classifications as it remains relatively consistent.
- This study demonstrates the importance of **spatially disaggregated emission data** for **effective environmental management** and **policy planning**. It highlights potential of **GIS** in understanding distribution of **road traffic emissions** and provides **sustainable urban development** perspectives.

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