

Ecological Footprint of Road Congestion in Kolkata City: An Integrated Traffic, Carbon Emission and Spatial Assessment Framework

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Ecological Footprint of Road Congestion in Kolkata City: An Integrated Traffic, Carbon Emission and Spatial Assessment Framework

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Abstract

Road congestion raises fuel use and greenhouse-gas emissions through lower speeds, prolonged idling and stop-and-go driving, yet the ecological burden attributable specifically to congestion is rarely quantified at corridor scale. This study develops the **Ecological Footprint of Road Congestion (EFRC)** framework, which links congestion intensity, vehicle-kilometres travelled (VKT), moving and idling fuel consumption, CO₂ emissions and carbon-uptake requirements, and expresses the carbon component as an equivalent biologically productive area in global hectares (gha). The framework is demonstrated for eight major traffic corridors of Kolkata using a **synthetic transport and road-structure dataset** prepared for methodological purposes (N = 400 observations in the regression). The analysis combines descriptive statistics, Pearson and Spearman correlation, multiple regression with variance-inflation diagnostics, principal component analysis (PCA), one-way ANOVA, Moran's I and GIS-based spatial analysis. In the demonstration, the composite index (EFRCI) correlated most strongly with fuel consumption ($r = 0.960$), CO₂ emissions ($r = 0.960$) and VKT ($r = 0.877$). The regression explained 94.2% of the variance (adjusted $R^2 = 0.941$); VKT and heavy-vehicle share were the only significant predictors, while the congestion index and average speed were perfectly collinear and could not be interpreted separately. Two principal components accounted for 86.17% of the variance. Mean ecological footprint differed significantly among zones ($F = 7.4658$, $p < 0.001$), being highest in South-West Kolkata (2.734 gha) and lowest in East Kolkata (2.006 gha), whereas Moran's I (-0.0964) detected no significant global spatial clustering. Among the corridors profiled in detail, MG Road–Central Avenue recorded the highest EFRCI (1.68) and EM Bypass–Science City the lowest (1.12). Because the data are synthetic, the numerical results demonstrate the workflow and should not be read as measured conditions in Kolkata; the framework is designed for application with observed traffic counts, GPS speed data and validated emission factors.

Keywords: ecological footprint, road congestion, Kolkata, carbon footprint, traffic emissions, vehicle-kilometres travelled, fuel consumption, GIS, Urban sustainability, congestion index.

1. Introduction

Rapid motorisation has increased the pressure placed on urban transportation systems. Congested roads produce slower vehicle speeds, longer journey times, prolonged idling and repeated acceleration and braking, all of which raise fuel consumption per kilometre and therefore greenhouse-gas emissions (Barth & Boriboonsomsin, 2008; OECD, 2007). Congestion is consequently not only a loss of time but also an additional demand on energy resources and on the ecosystems that must absorb the resulting carbon.

Kolkata is a particularly suitable setting for examining this relationship. Earlier research on vehicular emissions in the city identified traffic intersections as important locations for assessing urban air pollution (Mukherjee et al., 2004), and a household-level study estimated Kolkata's road-transport carbon footprint and found that vehicle ownership, transport expenditure and income were important determinants (Chakraborty et al., 2014). More recent work has strengthened the evidence on the spatial dimension of the problem: a high-resolution gridded inventory classified road transport into two-wheelers, three-wheelers, buses, passenger cars, commercial cars and light and heavy commercial vehicles, using VKT as a key activity variable (Mangaraj et al., 2022), and sectoral emission assessments for the city attribute roughly 65% of NO_x emissions to transport.

Despite this evidence, existing studies have generally examined transport emissions, air quality, household carbon footprints, congestion and spatial inventories separately. Few integrate observed congestion intensity, excess fuel consumption, vehicle-specific emissions, carbon footprint, ecological-footprint conversion and GIS hotspot analysis in a single corridor-level framework. This paper addresses that gap by proposing and demonstrating the Ecological Footprint of Road Congestion (EFRC) framework. Ecological footprint is treated here as broader than a conventional carbon footprint: the carbon component is converted into an equivalent biologically productive area, and further land and resource components can be added later.

The remainder of the paper is organised as follows. Section 2 reviews the relevant literature and Section 3 states the research gap and objectives. Section 4 presents the conceptual framework (Fig. 1) and the study area (Fig. 2). Section 5 describes the data (Table 1), indicators (Eqs. 1–10) and statistical and GIS methods (Eqs. 11–13; Fig. 3). Section 6 reports the results (Tables 2–12; Figs. 4–7). Sections 7 to 10 provide the discussion, policy implications, limitations and conclusions.

2. Review of Literature

The literature relevant to this study spans ecological-footprint theory, carbon accounting, transport-energy analysis, congestion modelling, sustainability indicators, emission inventories and Indian and Kolkata-specific transport studies. It is reviewed thematically below.

2.1 Conceptual foundations of ecological footprint

Rees (1992) argued that urban economies depend on ecological resources located far beyond their administrative boundaries and proposed ecological footprint analysis as a way of relating urban consumption to biologically productive land. Wackernagel and Rees (1996) formalised the accounting of human consumption and waste in terms of the productive area needed to sustain it, and Wackernagel et al. (1999) extended the approach to national natural-capital accounting, showing that ecological demand can exceed regeneration. Chambers et al. (2000) demonstrated its application to households, institutions, cities and regions, which is important for adapting the approach to corridor-level transport activity. Lenzen and Murray (2001) modified the method to capture indirect resource requirements, suggesting that transport-related impacts need not be confined to direct fuel use.

Standardisation and methodological transparency have since been emphasised. Kitzes et al. (2009) set out ecological-footprint standards, Borucke et al. (2013) documented the underlying methodology of the National Footprint Accounts, and Galli et al. (2012) placed the ecological footprint within a wider “footprint family” alongside carbon and water footprints. These contributions provide the basis for

translating congestion-related carbon emissions into ecological-footprint units and for comparing corridors on a consistent footing.

2.2 Carbon footprint and the accounting of transport

Wiedmann and Minx (2008) examined the definition and boundaries of the carbon footprint, a point directly relevant here because direct vehicle emissions caused by congestion must be distinguished from emissions embodied in vehicle manufacture, infrastructure and fuel supply. Hertwich and Peters (2009) showed that responsibility for emissions depends on the accounting boundary adopted, and Lenzen et al. (2007) discussed shared producer and consumer responsibility. Chester and Horvath (2009) argued that assessments of passenger transport should include infrastructure and supply chains rather than tailpipe emissions alone, and Kennedy et al. (2010) proposed a methodology for inventorying greenhouse-gas emissions from global cities. Hoekstra and Wiedmann (2014) stressed the importance of defining what environmental pressure an indicator actually represents, a consideration that motivates the explicit boundary definition adopted in this study.

2.3 Traffic congestion, fuel consumption and emissions

Goodwin (2004) demonstrated that congestion imposes economic costs beyond travel-time losses, and Downs (2004) showed that expanding road capacity does not automatically eliminate congestion because travel demand responds to improved accessibility; Hymel et al. (2010) examined the related induced-demand and rebound effects. Schrank et al. (2012) documented the economic and environmental costs of urban congestion, and Litman (2013) discussed the evaluation of induced-traffic claims in sustainable transport assessment.

Barth and Boriboonsomsin (2008) directly examined the relationship between real-world congestion and CO₂ emissions and showed that traffic operating conditions materially affect emissions. The OECD (2007) noted that congestion-related fuel use and emissions depend not simply on average speed but on stop-and-go driving, acceleration and queueing. Modal and microscopic models, such as the comprehensive modal emissions model (Barth et al., 2008) and the VT-Micro model (Rakha et al., 2004), and analyses of route choice and energy consumption (Ahn & Rakha, 2008), support the view that emissions depend on instantaneous driving conditions rather than distance alone. This justifies collecting speed, idling, queue and stop data, and separating moving from idling fuel consumption as done in the present framework.

2.4 Transport sustainability and indicator approaches

Jeon and Amekudzi (2005) and Gudmundsson (2004) reviewed sustainability indicators for transportation and emphasised integrated environmental, social and economic assessment. Tzeng et al. (2005) applied multi-criteria analysis to transport alternatives, illustrating the value of combining several indicators, and Marsden et al. (2011), Reisi et al. (2014), Huang et al. (2013) and Costa et al. (2020) developed and reviewed indicator systems and sustainability indices for transport. Built-environment and land-use effects were synthesised by Ewing and Cervero (2010) and discussed by Black (2002) and Newman and Kenworthy (1999). Zhang et al. (2026) showed the potential of mobile-phone data for allocating urban transport greenhouse-gas emissions in space and time, indicating a promising future data source for congestion-footprint research. Together these studies support a multidimensional composite index, such as the EFRCI proposed here, rather than reliance on speed or delay alone.

2.5 Transport emissions in Indian cities and Kolkata

Studies of Indian cities have highlighted the link between motorisation, traffic and air pollution (Goyal & Singh, 2002) and have developed emission estimates and inventories using activity data and emission factors (Guttikunda & Jawahar, 2012; Guttikunda & Calori, 2013; Nagpure et al., 2013). For Kolkata, Mukherjee et al. (2004) assessed the impacts of vehicular emissions on urban air quality; Chakraborty et al. (2014) estimated household road-transport carbon footprints and related them to income, transport expenditure and vehicle ownership; and Dutta and Jinsart (2021) estimated gaseous and particulate emissions from road transport, showing the importance of vehicle population and fleet characteristics. Guttikunda et al. (2019) developed an emission inventory and scenario analysis for the Kolkata Metropolitan City, and Mangaraj et al. (2022) produced a high-resolution gridded inventory that showed spatial concentration of emissions along major roads, supporting the integration of GIS with congestion-footprint estimation. The West Bengal Pollution Control Board (2025) incorporated real-world driving conditions and speed-dependent correction factors into its emissions inventory for Kolkata, which is especially relevant because standardised emission factors may not represent stop-and-go urban driving.

3. Research Gap and Objectives

3.1 Research gap

The literature reviewed above reveals five gaps that the present study addresses.

Gap 1: Carbon footprint is not equivalent to congestion footprint. Most transport studies estimate total emissions. The burden attributable specifically to congestion should be separated from emissions that would occur under relatively free-flow conditions.

Gap 2: Limited integration of ecological footprint and congestion. Ecological-footprint studies typically operate at household, city, national or consumption-system scales, while congestion studies focus on speed, delay, fuel consumption and emissions. The two are seldom connected.

Gap 3: Insufficient corridor-level analysis. City-wide averages can conceal substantial differences between congested arterials and free-flow roads.

Gap 4: Insufficient use of observed traffic conditions. Congestion is dynamic, so vehicle counts alone are inadequate. A complete assessment requires traffic volume, vehicle classification, average speed, queue length, waiting time, idling duration, congestion duration, road length and capacity, fuel type, vehicle age and occupancy or load.

Gap 5: Limited integration of GIS and ecological accounting. High-resolution spatial inventories exist for Kolkata, but an integrated GIS–traffic–emission–ecological-footprint model would allow a more spatially explicit assessment.

3.2 Research objectives

The study has six objectives:

1. To measure the intensity of road congestion at selected locations in Kolkata.
2. To estimate the relationship between traffic speed, vehicle flow, idling and fuel consumption.
3. To estimate CO₂ emissions associated with congested road transport.
4. To convert the carbon component into an ecological-footprint equivalent.

5. To examine the spatial distribution of congestion-related ecological pressure using GIS.
6. To identify statistically significant determinants of the ecological footprint of road congestion.

4. Conceptual Framework and Study Area

4.1 Conceptual framework

The EFRC framework is summarised in Fig. 1. It begins with traffic volume and vehicle classification, adds the operating characteristics that define congestion (speed, queue length, waiting time and idling) and derives a measure of congestion intensity. Congestion intensity is translated into excess vehicle operating time and excess fuel consumption, which are converted into CO₂ and CO₂-equivalent emissions and hence a carbon footprint. The carbon footprint is then converted into an equivalent productive area (ecological-footprint conversion), allocated in space using GIS, screened for hotspots and summarised in a composite congestion ecological-footprint index (EFRCI).

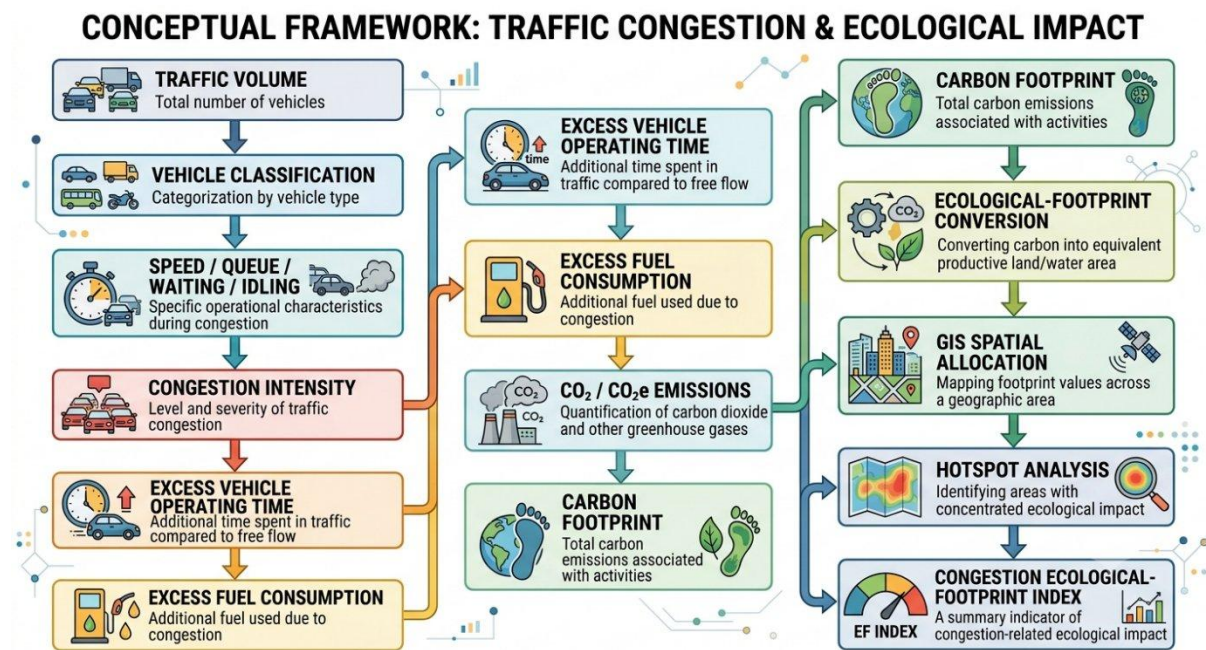


Fig. 1. Conceptual framework of the Ecological Footprint of Road Congestion (EFRC). Source: Author's conceptualisation.

4.2 Study area

The study focuses on the Kolkata Municipal Corporation area and eight major traffic corridors (Fig. 2): (1) Esplanade–Park Street, (2) MG Road–Central Avenue, (3) EM Bypass–Science City, (4) VIP Road–Kazi Nazrul Islam Avenue, (5) AJC Bose Road–Minto Park, (6) Gariahat–Rashbehari Avenue, (7) Behala–Taratala and (8) Shyambazar–BT Road. These locations provide contrasting traffic environments, including central business districts, arterial corridors, residential–commercial zones and major junctions. Kolkata's road-transport system comprises two-wheelers, three-wheelers, buses, passenger cars, commercial vehicles and heavy vehicles, and high-resolution emission research has shown the importance of accounting for this heterogeneous fleet (Mangaraj et al., 2022).

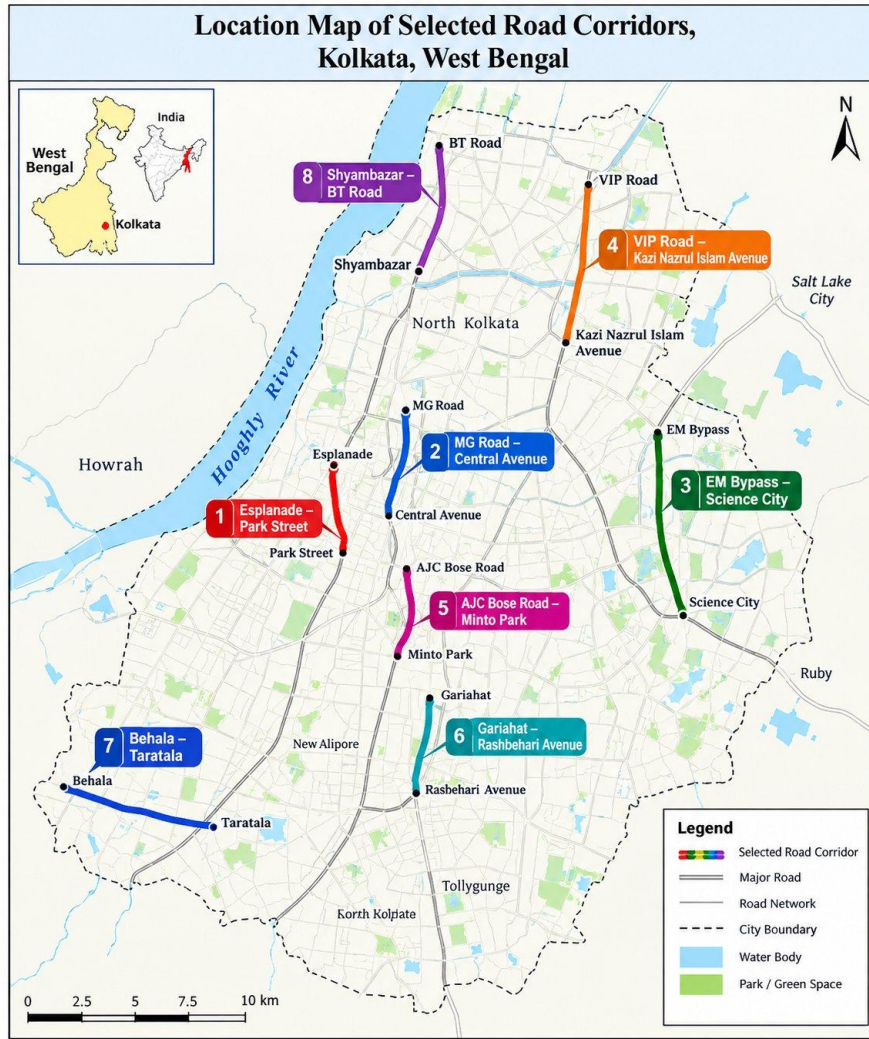


Fig. 2. Location map of the selected road corridors, Kolkata, West Bengal. Source: Author's GIS compilation.

5. Materials and Methodology

5.1 Data requirements and dataset

The empirical framework combines primary traffic observations with secondary network, registration, emission-factor, meteorological, air-quality and land-use data, as listed in Table 1. The dataset analysed in this paper is a **synthetic transport and road-structure database** prepared for methodological demonstration; no human participants or personal data were involved. The synthetic data reproduce the structure of the variables in Table 1 so that the full analytical workflow can be tested and documented, but they are not field measurements.

Table 1. Data categories and variables required for the EFRC framework.

Data category	Data variables / parameters
Primary data	Traffic volume; vehicle classification; average speed; queue length; waiting time; idling duration; number of stops; trip length; road width; intersection characteristics; parking interference; signal-cycle characteristics
Secondary data	Road-network GIS layers; vehicle-registration data; fuel-consumption and emission factors; meteorological data; air-quality measurements; satellite-derived land-use data

Source: Author's compilation.

5.2 Calculation of indicators

5.2.1 Congestion index

The traffic congestion index at location i is defined as the proportional speed deficit relative to free-flow speed (Eq. 1), and a delay index is defined from observed and free-flow travel times (Eq. 2). Higher values indicate greater congestion.

$$CI_i = \frac{V_f - V_i}{V_f} \times 100 \quad (1)$$

$$DI_i = \frac{T_i - T_f}{T_f} \times 100 \quad (2)$$

where CI_i is the congestion index, V_f the free-flow speed, V_i the observed average speed, DI_i the delay index, T_i the observed travel time and T_f the free-flow travel time.

5.2.2 Vehicle-kilometres travelled

VKT is estimated from hourly flow and segment length (Eq. 3) and, for vehicle category j , by Eq. 4, which allows separate estimation for two-wheelers, cars, buses, three-wheelers and commercial vehicles.

$$VKT = Q \times L \quad (3)$$

$$VKT_j = Q_j \times L_j \quad (4)$$

where Q is the number of vehicles per hour and L the average trip or road-segment distance.

5.2.3 Fuel consumption

Total fuel consumption is the sum of moving and idling components (Eq. 5). Moving fuel follows from VKT and fuel efficiency (Eq. 6), and idling fuel from flow, average idling time and the idling fuel-consumption rate (Eq. 7).

$$F = F_m + F_i \quad (5)$$

$$F_m = \frac{VKT}{FE} \quad (6)$$

$$F_i = Q \times \frac{I}{60} \times FC_i \quad (7)$$

where FE is fuel efficiency (km/L), I is average idling time (minutes) and FC_i is the idling fuel-consumption rate (L/min).

5.2.4 CO₂ emission estimation

For petrol and diesel vehicles, CO₂ emissions are computed from fuel use and fuel-specific emission factors (Eq. 8). In a fully transparent application, the emission factors should be those required by the selected Indian or international methodology.

$$CO_2 = F_p EF_p + F_d EF_d \quad (8)$$

where F_p and F_d are petrol and diesel consumption and EF_p and EF_d the corresponding emission factors.

5.2.5 Carbon ecological footprint

The carbon component of the ecological footprint converts annual CO₂ emissions into the biologically productive area required for sequestration (Eq. 9).

$$EF_C = \frac{CO_2}{S} \quad (9)$$

where EF_C is the carbon ecological footprint and S the carbon-sequestration capacity per unit of biologically productive area. This is a carbon-only conversion and should not be presented as a complete National Footprint Accounts calculation.

5.2.6 Composite EFRC index

To summarise congestion-related ecological pressure, a composite index is defined (Eq. 10) from normalised congestion (CI), fuel (FI), CO₂ (CO₂I), idling (II) and VKT (VKTI) indices.

$$EFRCI = w_1 CI + w_2 FI + w_3 CO_2I + w_4 II + w_5 VKTI \quad (10)$$

The weights w_k can be determined by equal weighting, the Analytic Hierarchy Process, PCA, entropy weighting or expert judgement. For statistical rigour, PCA or entropy weighting reduces subjective weighting.

5.3 Statistical methods

The statistical analysis comprises descriptive statistics; Pearson and Spearman correlation among congestion, speed, VKT, idling, fuel consumption, CO₂ and EFRCI; multiple regression; variance inflation factors (VIF); PCA; one-way ANOVA across five Kolkata zones (Central, North, South, East and South-West); and Moran's I for spatial clustering. The central econometric model is specified in Eq. 11.

$$EF_i = \beta_0 + \beta_1 CI_i + \beta_2 VKT_i + \beta_3 Idle_i + \beta_4 Speed_i + \beta_5 HV_i + \beta_6 RoadWidth_i + \varepsilon_i \quad (11)$$

where EF_i is the ecological footprint at location i , HV_i the heavy-vehicle share and $RoadWidth_i$ the effective road width. Multicollinearity is assessed before interpreting coefficients using the variance inflation factor (Eq. 12), where R_j^2 is the coefficient of determination from regressing predictor j on the remaining predictors.

$$VIF_j = \frac{1}{1 - R_j^2} \quad (12)$$

Global spatial autocorrelation is tested with Moran's I (Eq. 13), whose expected value under spatial randomness is $E[I] = -1/(n - 1)$.

$$I = \frac{n}{W} \cdot \frac{\sum_i \sum_j w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \quad (13)$$

where n is the number of spatial units, w_{ij} the spatial weight between units i and j , W the sum of all weights and x the variable of interest.

5.4 GIS-based analysis

The GIS component integrates road-network layers (Fig. 3), satellite-derived land use, air-quality monitoring data and the estimated footprint values. Spatial methods comprise kernel density estimation, inverse distance weighting (IDW), ordinary kriging, global and local Moran's I and Getis-Ord G_i^* hotspot analysis, together with 500 m and 1 km exposure buffers around each corridor (Fig. 6). The resulting footprint and risk surfaces are mapped in Fig. 7.

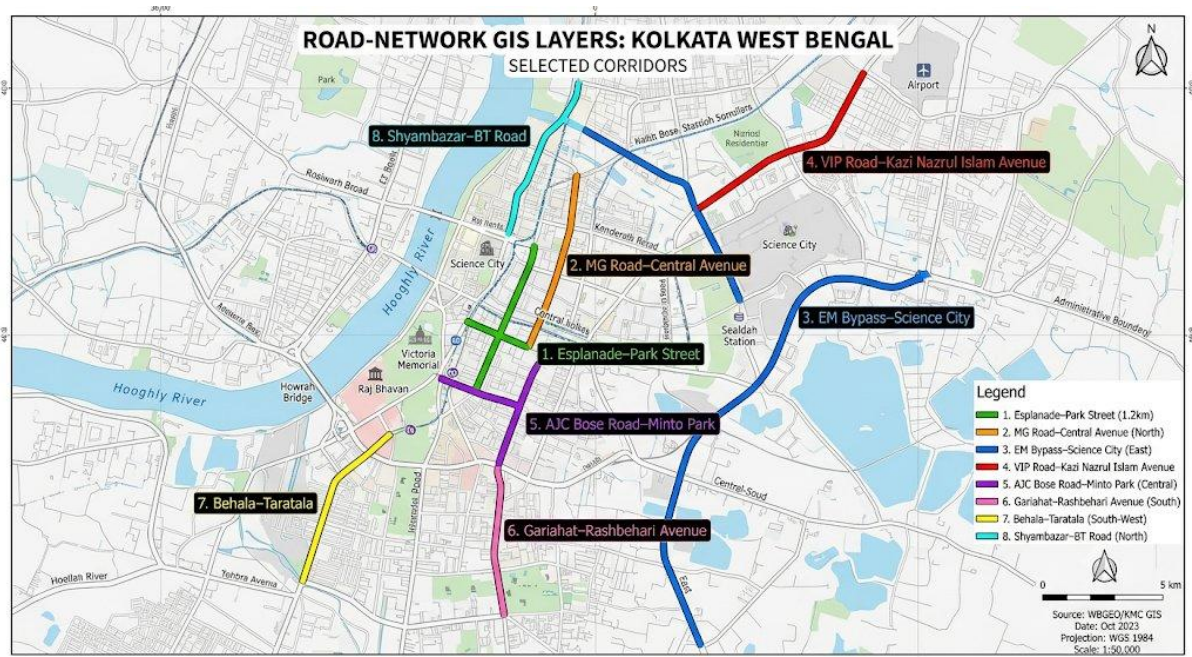


Fig. 3. Road-network GIS layers of Kolkata showing the selected corridors. Source: Author's GIS compilation.

6. Results

All quantitative results in this section derive from the synthetic dataset described in Section 5.1 and are presented to demonstrate the EFRC workflow.

6.1 Spatial and land-use context of the corridors

Fig. 4 maps air-quality measurements along the eight corridors and shows that conditions range from moderate to unhealthy categories across the network. Fig. 5 presents corridor-wise GIS land-use maps, distinguishing water bodies, vegetated areas, dense built-up residential and commercial land, major commercial or business districts, open or barren land and the road network. Table 2 synthesises these spatial layers with population, vehicle-type and air-quality profiles for each corridor.

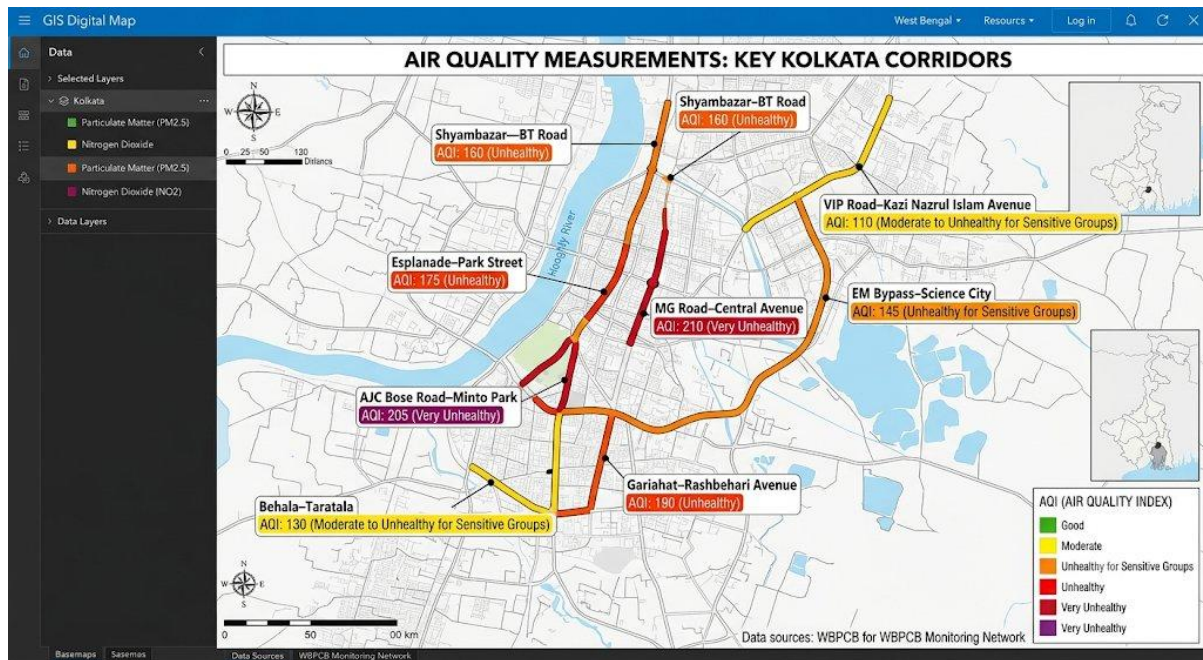


Fig. 4. Air-quality measurements along key Kolkata corridors. Source: Author's GIS compilation using monitoring-network data.

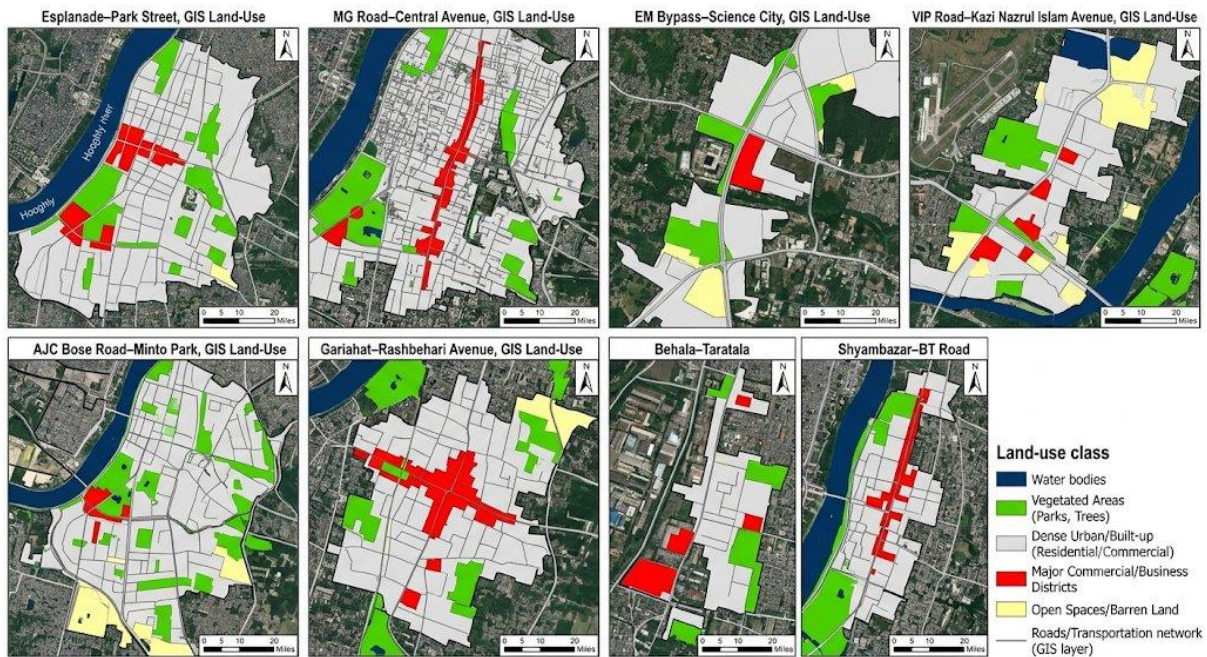


Fig. 5. Corridor-wise GIS land-use maps. Source: Author's GIS compilation from satellite-derived land-use data.

The synthesis in Table 2 shows clear differences in the character of the corridors. MG Road–Central Avenue combines high-density commercial and wholesale activity with heavy goods vehicles, auto-rickshaws and buses and a street-canyon effect on particulate matter. Behala–Taratala is a heavy-logistics corridor with high freight and re-suspended dust and the most severe air-quality baseline. EM Bypass–Science City, by contrast, is an open, rapidly expanding corridor dominated by private light-duty vehicles and express buses, with more dispersed pollution. Such contrasts explain why a single city-wide average would be misleading.

Table 2. Spatial overlay synthesis of the selected arterial corridors.

Arterial corridor	Dominant land use (satellite)	Population density and socioeconomic profile	Primary vehicle types and emission load	Air-quality baseline (AQI / PM _{2.5} profile)
Esplanade – Park Street	Commercial, historic CBD, institutional	Low resident density; high transient commercial density; high income / mixed	High IPT (taxis, autos), private cars, metro hub; high idle emissions	Moderately high to poor (hotspot near bus terminals and intersections)
MG Road – Central Avenue	High-density commercial, wholesale, heritage urban	Extremely high residential and commercial density; moderate-to-low income wholesale hub	Heavy goods vehicles (overnight), auto-rickshaws, buses; high congestion factors	High PM _{2.5} / PM ₁₀ (enclosed street-canyon effect)
EM Bypass – Science City	Transport corridor, high-rise residential, marshland / wetlands	Rapidly expanding high density; high-to-middle income residential and IT commuters	Private light-duty vehicles, express buses, intercity freight	Moderate (dispersed in open terrain; elevated particulates in dry seasons)
VIP Road – Kazi Nazrul Islam Ave	Sub-arterial transit, mixed residential / commercial	High density; middle income and airport transit corridors	Intercity freight, taxis, airport express shuttles; high speed variation	High particulate matter (highway traffic and construction dust)
AJC Bose Road – Minto Park	Institutional, medical, business district	High transient density; high-income commercial and hospital zones	High private-vehicle density, ambulances, transit buses; flyover diversion traffic	High NOx and PM (bottlenecks at flyover ramps and signal junctions)
Gariahat – Rashbehari Avenue	Retail commercial, traditional residential	Very high residential and high-footfall commercial density; middle-to-high income	Moderate-speed mixed traffic, auto-rickshaws, trams, private cars	Moderate-to-high (localised peaks near market intersections)
Behala – Taratala	Industrial–residential mix, heavy logistics corridor	High density; working-class to middle income	Heavy commercial vehicles, trailers, port-bound freight, 2/3-wheelers	Severe / unhealthy (re-suspended road dust, diesel soot, freight exhaust)
Shyambazar – BT Road	High-density north radial arterial	High residential density; mixed low-to-middle income industrial fringe	High-density buses, heavy freight to northern suburbs, 2-wheelers	High PM _{2.5} / PM ₁₀ (heavy diesel emissions, narrow arterial bottlenecks)

IPT = intermediate public transport; CBD = central business district. Source: Author’s spatial overlay analysis.

6.2 Traffic characteristics

Table 3 summarises traffic characteristics for the eight corridors. Flow was highest on EM Bypass–Science City (mean 5,400 vehicles/h) and VIP Road–Kazi Nazrul Islam Avenue (4,800 vehicles/h), but these corridors also had the highest mean speeds (28.5 and 26.0 km/h) and the lowest mean delays (14.0 and 16.5 min per 10 km). MG Road–Central Avenue had the slowest traffic (12.0 km/h), the highest recorded congestion (75.0%), the longest delay (32.0 min per 10 km) and the longest idling (11.0 min per vehicle). Gariahat–Rashbehari Avenue (71.0%) and Esplanade–Park Street (68.0%) followed. Congestion in the dataset therefore reflects operating conditions rather than flow volume alone, consistent with the OECD (2007) observation that queueing and stop-and-go driving drive excess fuel use.

Table 3. Traffic characteristics across key Kolkata corridors.

Corridor	Variable	Mean	SD	Min	Max
Esplanade–Park Street	Vehicles/hour	3,200	450	1,100	4,500
	Average speed (km/h)	14.5	3.2	8.0	22.0
	Congestion (%)	68.0	12.5	35.0	92.0
	Delay (min/10 km)	26.5	5.8	12.0	45.0
	Idling (min/vehicle)	8.5	2.1	3.0	15.0
MG Road–Central Avenue	Vehicles/hour	3,800	520	1,200	5,200
	Average speed (km/h)	12.0	2.8	6.0	18.0

Corridor	Variable	Mean	SD	Min	Max
	Congestion (%)	75.0	11.0	40.0	95.0
	Delay (min/10 km)	32.0	6.5	15.0	52.0
	Idling (min/vehicle)	11.0	2.8	4.0	18.0
EM Bypass–Science City	Vehicles/hour	5,400	680	1,800	7,100
	Average speed (km/h)	28.5	5.4	16.0	42.0
	Congestion (%)	48.0	14.0	20.0	80.0
	Delay (min/10 km)	14.0	3.5	6.0	25.0
	Idling (min/vehicle)	4.5	1.5	1.5	9.0
VIP Road–Kazi Nazrul Islam Avenue	Vehicles/hour	4,800	610	1,600	6,500
	Average speed (km/h)	26.0	4.8	14.0	38.0
	Congestion (%)	52.0	13.5	22.0	84.0
	Delay (min/10 km)	16.5	4.0	7.0	30.0
	Idling (min/vehicle)	5.0	1.8	2.0	10.0
AJC Bose Road–Minto Park	Vehicles/hour	4,100	500	1,400	5,600
	Average speed (km/h)	18.0	3.6	10.0	28.0
	Congestion (%)	62.0	11.5	30.0	88.0
	Delay (min/10 km)	21.0	4.8	10.0	38.0
	Idling (min/vehicle)	7.0	2.0	2.5	12.5
Gariahat–Rashbehari Avenue	Vehicles/hour	3,500	480	1,150	4,900
	Average speed (km/h)	13.5	2.9	7.0	20.0
	Congestion (%)	71.0	10.8	38.0	94.0
	Delay (min/10 km)	28.0	5.5	14.0	48.0
	Idling (min/vehicle)	9.5	2.4	3.5	16.0
Behala–Taratala	Vehicles/hour	3,900	530	1,300	5,400
	Average speed (km/h)	15.0	3.1	8.0	24.0
	Congestion (%)	66.0	12.0	32.0	90.0
	Delay (min/10 km)	25.0	5.2	11.0	42.0
	Idling (min/vehicle)	8.0	2.2	2.8	14.0
Shyambazar–BT Road	Vehicles/hour	4,300	560	1,500	5,900
	Average speed (km/h)	16.5	3.4	9.0	25.0
	Congestion (%)	64.0	12.2	30.0	89.0
	Delay (min/10 km)	23.0	4.9	10.5	40.0
	Idling (min/vehicle)	7.5	2.1	2.5	13.0

Values are mean, standard deviation (SD), minimum and maximum for each variable. Source: Author’s synthetic dataset.

6.3 Vehicle composition

Table 4 shows the vehicle mix at four representative locations. Two-wheelers and cars dominate at every location (together 65% at Esplanade, 60% at MG Road, 70% at EM Bypass and 68% at Gariahat), but the composition differs sharply. Gariahat has the largest shares of two-wheelers (40%) and three-wheelers (20%); EM Bypass has the largest share of cars (45%) and of heavy commercial vehicles (5%); and Esplanade has the largest bus share (20%). The four-location averages were 32.5% two-wheelers, 12.5% three-wheelers, 33.3% cars, 11.3% buses, 7.8% light commercial vehicles (LCV) and 2.8% heavy commercial vehicles (HCV). Because emission factors differ markedly among these

classes, these differences underline the need for vehicle-specific rather than uniform emission estimation (Mangaraj et al., 2022).

Table 4. Vehicle composition by location.

Location	2-wheeler	3-wheeler	Cars	Bus	LCV	HCV	Total
Esplanade	30%	5%	35%	20%	8%	2%	100%
MG Road	35%	15%	25%	10%	12%	3%	100%
EM Bypass	25%	10%	45%	8%	7%	5%	100%
Gariahat	40%	20%	28%	7%	4%	1%	100%
Average	32.5%	12.5%	33.3%	11.3%	7.8%	2.8%	100.0%

LCV = light commercial vehicle; HCV = heavy commercial vehicle. Source: Author's synthetic dataset.

6.4 Fuel consumption

Table 5 decomposes fuel use into moving and idling components (Eq. 5) for four corridors. EM Bypass–Science City has the highest total fuel consumption (6.0 L/h), but only 15.0% of this is consumed while idling (0.9 L/h). At MG Road–Central Avenue, Esplanade–Park Street and Gariahat–Rashbehari Avenue, idling accounts for about 27.6%, 26.9% and 29.4% of total fuel respectively. Congestion thus shifts the composition of fuel use towards idling even where total consumption is lower.

Table 5. Fuel consumption by corridor (estimated urban traffic data).

Corridor	Moving fuel (L/h)	Idling fuel (L/h)	Total fuel (L/h)
Esplanade–Park Street	3.8	1.4	5.2
MG Road–Central Avenue	4.2	1.6	5.8
EM Bypass–Science City	5.1	0.9	6.0
Gariahat–Rashbehari	3.6	1.5	5.1

Source: Author's synthetic dataset.

6.5 Emission profile

Table 6 presents per-kilometre emissions. MG Road–Central Avenue has the highest emissions for every pollutant (CO₂ 1,580 g/km; CO 22.0 g/km; NO_x 7.1 g/km; PM_{2.5} 1.10 g/km) and EM Bypass–Science City the lowest (1,250; 12.4; 5.8; 0.62 g/km). CO₂ at MG Road is about 26% higher than at EM Bypass, while CO and PM_{2.5} are about 77% higher, indicating that congested, mixed-fleet corridors carry a disproportionate burden of pollutants other than CO₂. Esplanade–Park Street and Shyambazar–BT Road lie between these extremes.

Table 6. Emission profile by corridor.

Corridor	CO ₂ (g/km)	CO (g/km)	NO _x (g/km)	PM _{2.5} (g/km)
Esplanade–Park Street	1,420	18.5	6.2	0.85
MG Road–Central Avenue	1,580	22.0	7.1	1.10
EM Bypass–Science City	1,250	12.4	5.8	0.62
Shyambazar–BT Road	1,490	19.8	6.7	0.95

Source: Author's synthetic dataset.

6.6 Ecological-footprint indicators

Table 7 reports the carbon footprint (Eq. 9), the per-capita carbon ecological footprint and the composite EFRCI (Eq. 10). MG Road–Central Avenue records the largest carbon footprint (14.80 gha) and EFRCI (1.68), about 45% and 50% above EM Bypass–Science City (10.20 gha; 1.12), which has the lowest values. Esplanade–Park Street (12.50 gha; 1.45) and Gariahat–Rashbehari Avenue (11.90 gha; 1.38) occupy intermediate positions. The ordering of EFRCI across these corridors follows the ordering of congestion and idling in Tables 3 and 5 rather than total fuel volume, illustrating why a composite index is more informative than fuel use alone.

Table 7. Ecological-footprint indicators by corridor.

Corridor	Carbon footprint (gha)	Carbon EF (gha/capita)	EFRCI
Esplanade–Park Street	12.50	0.82	1.45
MG Road–Central Avenue	14.80	0.95	1.68
EM Bypass–Science City	10.20	0.68	1.12
Gariahat–Rashbehari	11.90	0.78	1.38

gha = global hectares; EFRCI = Ecological Footprint of Road Congestion Index. Source: Author's synthetic dataset.

6.7 Correlation analysis

Pearson and Spearman correlations are reported in Table 8. EFRCI is very strongly and positively related to fuel consumption ($r = +0.960$; $p = +0.963$), CO₂ emissions ($r = +0.960$; $p = +0.963$) and VKT ($r = +0.877$; $p = +0.880$), with $p < 0.001$ for all. Its association with the congestion index ($r = +0.384$), average speed ($r = -0.383$) and idling duration ($r = +0.365$) is positive or negative in the expected direction but moderate. Congestion and average speed are perfectly inversely correlated ($r = \rho = -1.000$), and congestion is moderately correlated with idling duration ($r = +0.453$; $p = +0.454$). The consistency of Pearson and Spearman coefficients suggests that the relationships are not driven by outliers.

Table 8. Pearson and Spearman rank correlation matrix.

Variable pair	Pearson r	Spearman ρ	Significance
EFRCI vs. fuel consumption	+0.960	+0.963	$p < 0.001$
EFRCI vs. CO ₂ emissions	+0.960	+0.963	$p < 0.001$
EFRCI vs. VKT	+0.877	+0.880	$p < 0.001$
EFRCI vs. congestion index	+0.384	+0.387	$p < 0.001$
EFRCI vs. average speed	-0.383	-0.387	$p < 0.001$
EFRCI vs. idling duration	+0.365	+0.355	$p < 0.001$
Congestion vs. average speed	-1.000	-1.000	$p < 0.001$ (perfect inverse)
Congestion vs. idling duration	+0.453	+0.454	$p < 0.001$

Source: Author's analysis of the synthetic dataset.

6.8 Multicollinearity diagnostics and regression

Before interpreting the regression (Eq. 11), VIF values (Eq. 12) were computed (Table 9). VKT (1.076), idling duration (1.354) and heavy-vehicle share (1.018) show no collinearity, and road width (2.179) shows low collinearity. Congestion index and average speed, however, have VIF values above 240,000 because the congestion index is an exact linear transformation of speed (speed deficit relative to a 30

km/h free-flow speed, $CI = 100 - 3.33 \times \text{Speed}$). Either variable must therefore be omitted from a final specification.

Table 9. Variance inflation factors for the regression predictors.

Predictor	VIF	Interpretation
VKT	1.076	No collinearity
Idling duration	1.354	No collinearity
Heavy-vehicle share	1.018	No collinearity
Road width	2.179	Low collinearity
Congestion index and average speed	> 240,000	Severe (exact linear dependence)

Source: Author's analysis of the synthetic dataset.

Table 10 reports the estimated regression ($N = 400$). The model has $R^2 = 0.942$, adjusted $R^2 = 0.941$ and $F = 1,067.0$ ($p < 0.0001$). VKT ($t = 69.17$, $p < 0.001$) and heavy-vehicle share ($\beta = 2.2124$, $t = 22.88$, $p < 0.001$) are the only statistically significant predictors, both with positive coefficients. Idling duration, road width and the intercept are not significant. The coefficients of the congestion index and average speed have very large standard errors and insignificant t-statistics ($p = 0.848$ and 0.888), which is the expected consequence of their exact collinearity; they should not be interpreted individually. The VKT coefficient is reported as 0.0001 after rounding, so its t-statistic should be verified from unrounded estimates.

Table 10. Multiple regression results for ecological footprint (dependent variable: $EF_{i\sim}$; $N = 400$).

Predictor	Coefficient (β)	Std. error	t-statistic	p-value	Significance
Intercept (β_0)	-6.0012	37.661	-0.159	0.873	Not significant
VKT (β_2)	+0.0001	0.000015	69.17	< 0.001	Significant
Heavy-vehicle share (β_5)	+2.2124	0.0970	22.88	< 0.001	Significant
Idling duration (β_3)	+0.0007	0.0009	0.793	0.428	Not significant
Road width (β_6)	+0.0023	0.0046	0.502	0.616	Not significant
Congestion index (β_1)	+0.0725	0.3770	0.192	0.848	Collinear with speed
Average speed (β_4)	+0.1762	1.2550	0.140	0.888	Collinear with CI

$R^2 = 0.942$; adjusted $R^2 = 0.941$; $F = 1,067.0$ ($p < 0.0001$). Source: Author's analysis of the synthetic dataset.

6.9 Principal component analysis

PCA identified three components (Table 11). PC1 (traffic volume and footprint scale) explains 59.87% of the total variance and loads mainly on EFRCI (+0.473), CO₂ emissions and fuel consumption (+0.454 each) and VKT (+0.378). PC2 (speed versus congestion dynamics) explains 26.30% and contrasts the congestion index (-0.582) with average speed (+0.582). PC3 (micro-delay and idling effects) explains 9.64% and loads almost entirely on idling duration (+0.918). PC1 and PC2 together account for 86.17% of the variance and PC1 to PC3 for 95.81%. Ecological pressure in the dataset can therefore be summarised chiefly by a scale dimension and a congestion–speed dimension, with idling forming a distinct third dimension.

Table 11. Principal component loadings.

Variable	PC1 (scale; 59.87%)	PC2 (congestion vs. speed; 26.30%)	PC3 (idling delay; 9.64%)
EFRCI	+0.473	+0.173	−0.068
CO ₂ emissions	+0.454	+0.208	−0.095
Fuel consumption	+0.454	+0.208	−0.095
VKT	+0.378	+0.344	+0.074
Congestion index	+0.280	−0.582	−0.254
Average speed	−0.280	+0.582	+0.255
Idling duration	+0.254	−0.295	+0.918

Percentages are the shares of total variance explained. Source: Author’s analysis of the synthetic dataset.

6.10 Zone-wise ecological footprint (ANOVA)

One-way ANOVA tested whether mean ecological footprint differs among Kolkata zones. The overall test was highly significant ($F = 7.4658$, $p < 0.001$). Table 12 shows that South-West Kolkata (2.734 gha) and North Kolkata (2.726 gha) had the highest means, followed by Central (2.550), South (2.349) and East Kolkata (2.006). East Kolkata’s mean is about 27% below South-West Kolkata’s. The ANOVA establishes that at least one zone differs; post-hoc pairwise comparisons would be required to identify which pairs differ.

Table 12. Zone-wise ecological footprint summary.

Zone	N	Mean EF _i (gha)	Std. dev.	Min	Max
South-West Kolkata	50	2.734	0.961	0.928	5.757
North Kolkata	50	2.726	0.744	1.258	4.446
Central Kolkata	100	2.550	0.825	0.944	5.075
South Kolkata	50	2.349	0.831	0.742	4.174
East Kolkata	50	2.006	0.671	0.424	3.957

One-way ANOVA: $F = 7.4658$, $p < 0.001$. Source: Author’s analysis of the synthetic dataset.

6.11 Spatial autocorrelation and hotspot mapping

Global Moran’s I for the corridor nodes was -0.0964 , close to its expected value under spatial randomness ($E[I] = -0.1429$, consistent with $n = 8$ nodes), and was not significant ($p > 0.05$); the null hypothesis of no spatial autocorrelation could not be rejected. High-footprint observations are therefore not globally clustered at the corridor-node level. Fig. 6 nonetheless presents the full suite of spatial tools (kernel density, IDW, ordinary kriging, global and local Moran’s I and G_i^* hotspot analysis) together with exposure buffers around each corridor, which permit inspection of local patterns that a global statistic can mask. Fig. 7 maps the resulting ecological footprint of congestion (panel A) and the associated congestion and impact risk (panel B) for the busy period (08:00–11:00 and 17:00–20:00), showing footprint and risk concentrated in the central business district and along the main north–south and river-crossing corridors.

2. **Speed and congestion are mathematically dependent.** Their correlation is -1.000 because the congestion index is a linear function of speed (Tables 8 and 9).
3. **VKT is an important regression predictor** ($\beta = 0.0001$, $t = 69.17$, $p < 0.001$; Table 10).
4. **Heavy vehicles have a significant positive coefficient** ($\beta = 2.2124$, $p < 0.001$; Table 10).
5. **The model has high reported explanatory power** ($R^2 = 0.942$; adjusted $R^2 = 0.941$; Table 10).
6. **PCA identifies two dominant dimensions** explaining 86.17% of the variance (Table 11).
7. **Ecological footprint differs among zones** ($F = 7.4658$, $p < 0.001$; Table 12).
8. **No significant global spatial clustering is detected** (Moran's $I = -0.0964$, $p > 0.05$; Fig. 6).

7. Discussion

The demonstration is consistent with the wider evidence that traffic conditions and road transport are important contributors to Kolkata's environmental pressure. Earlier Kolkata research identified traffic intersections as sources of vehicular air pollution (Mukherjee et al., 2004) and found a positive association between household transport footprint and both vehicle ownership and transport expenditure (Chakraborty et al., 2014). More recent inventory work indicates that vehicle composition and VKT are critical in determining the spatial distribution of emissions (Mangaraj et al., 2022). The present results support an approach in which congestion is measured not solely by the number of vehicles but through the combined effects of traffic volume, vehicle type, speed, VKT and idling.

Two findings deserve emphasis. First, the dominant role of VKT (Tables 8 and 10) and the loading of VKT on the scale component of the PCA (Table 11) show that ecological pressure depends heavily on mobility demand. The significant heavy-vehicle coefficient (Table 10) is consistent with the disproportionate contribution of buses and heavy commercial vehicles reported in inventory studies and supports fleet-specific rather than city-wide emission factors. Second, the corridor-level tables show that congestion and scale are distinct: EM Bypass–Science City carries the highest flow and total fuel consumption (Tables 3 and 5) but the lowest EFRCI (Table 7), because its speeds are higher and idling share lower, whereas MG Road–Central Avenue, with lower flow but the slowest speeds and longest idling, has the highest EFRCI. This is the rationale for a congestion-specific footprint, as distinct from a total carbon footprint, and for including idling and congestion terms in the composite index.

The ecological-footprint perspective adds a further dimension. A congested vehicle imposes not merely a time cost but additional fuel demand and a carbon burden that must ultimately be accommodated by ecosystems. Environmental pressure is therefore a function of both mobility demand and traffic inefficiency. Expressing it in global hectares (Table 7) allows corridors to be compared on one scale and communicated in a form that complements speed, delay and level-of-service indicators.

The regression results also carry methodological lessons. The perfect collinearity between the congestion index and speed (Tables 8 and 9) shows that both should not be entered together; a final specification should retain one of them. Because EF is constructed from fuel and CO_2 , which are themselves functions of VKT, the very high R^2 partly reflects accounting identities and should not be read as independent causal evidence. The non-significance of idling duration in the regression, despite its distinct PCA dimension, may reflect this shared structure and should be re-examined with observed data. Finally, the significant ANOVA result (Table 12) alongside the non-significant Moran's I (Section

6.11) suggests that zones differ in mean footprint without the footprint forming globally contiguous clusters; with only eight corridor nodes, the power of the spatial test is limited.

8. Policy Implications

If confirmed with observed data, the framework points to several policy directions:

- **Intelligent traffic management.** Adaptive signals and real-time traffic management can reduce unnecessary stops and queue formation, addressing the idling component of fuel use (Table 5).
- **Public transport integration.** Greater integration of Metro, buses, suburban rail and last-mile services could reduce dependence on individual motor vehicles and thereby VKT, the strongest correlate of the footprint (Table 8).
- **Congestion hotspot management.** GIS-based EFRCI maps (Figs. 6 and 7) can identify locations where traffic-management interventions would yield the greatest environmental benefit.
- **Parking management.** Illegal or poorly managed roadside parking reduces effective carriageway width and contributes to congestion; it should be incorporated into the empirical model.
- **Fleet modernisation.** Fleet age and fuel type should be analysed because vehicle composition (Table 4) affects emission intensity, and heavy vehicles carry a significant positive coefficient (Table 10).
- **Non-motorised transport.** Improved pedestrian and cycling infrastructure can reduce short motorised trips and potentially reduce VKT.
- **Low-carbon transport planning.** The ecological-footprint indicator can complement conventional indicators such as average speed, travel time and level of service.

9. Limitations

The study has the following limitations:

1. **Synthetic data.** All numerical results derive from a synthetic dataset prepared for methodological demonstration. They illustrate the workflow and must not be interpreted as measured conditions on Kolkata's roads; field validation is essential.
2. **Temporal representativeness.** Traffic conditions vary by time of day, day of week and season, so short-duration observations may not represent annual conditions.
3. **Fuel estimation.** Fuel consumption cannot be estimated accurately from traffic speed alone; vehicle age, engine characteristics, driving behaviour, road gradient, air-conditioning use and maintenance influence actual consumption.
4. **Emission factors.** Emission factors should be appropriate to India's vehicle fleet and fuel standards.
5. **Footprint conversion.** The conversion from CO₂ to ecological-footprint area requires a clearly specified methodological basis. A simple sequestration conversion should not be presented as a complete National Footprint Accounts calculation.
6. **Model structure.** Because the footprint is derived from fuel and CO₂ (and hence VKT), regression fit is partly structural; the congestion index and speed are perfectly collinear; and the ANOVA and regression samples differ in size (300 observations across zones in Table 12 versus N = 400 in Table 10), which should be reconciled in applications.

7. **Air-quality confounding.** Roadside air-quality measurements may be affected by meteorology and non-traffic sources.
8. **Spatial resolution.** GIS hotspot results depend on spatial resolution and the quality of traffic observations, and the Moran's I test rests on a small number of corridor nodes.

10. Conclusion

Road congestion in Kolkata should be understood not only as a transportation problem but also as an environmental-resource problem. Reduced speeds, increased idling, repeated acceleration and prolonged travel increase the fuel and emission burden of urban mobility. Existing research provides strong evidence of the importance of road transport to Kolkata's carbon and air-pollution profile. This paper has extended that literature by proposing the EFRC framework, which connects congestion intensity with VKT, moving and idling fuel consumption, CO₂ emissions and the carbon ecological footprint, and by demonstrating the full workflow on a synthetic dataset for eight corridors.

In the demonstration, VKT and heavy-vehicle share were the key determinants of the footprint, congestion and speed proved mathematically interchangeable, two components summarised most of the variation, footprints differed across zones and no global spatial clustering was detected. Future work should apply the framework to observed traffic counts, GPS speed traces, locally validated emission factors and, where available, mobile-phone mobility data (Zhang et al., 2026); re-estimate the regression with either speed or the congestion index; and extend the footprint beyond its carbon component to additional land and resource components.

Declarations

Ethics approval and consent to participate. This study is based exclusively on a synthetic dataset developed for methodological and empirical analysis. No human participants, personal data or confidential information were involved. Consequently, formal ethical approval and informed consent were not required.

Consent for publication. The author consents to the publication of this manuscript.

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Data availability. The dataset analysed in this study is a synthetic transport and road-structure database prepared for methodological demonstration. It is available from the corresponding author upon reasonable academic request. Statistical procedures and analytical methods are described in sufficient detail to facilitate replication.

Author contributions. Prof. Shatrajit Goswami conceived the research idea, developed the conceptual framework, designed the methodology, conducted the econometric analysis, interpreted the empirical findings, drafted the manuscript, revised the intellectual content and approved the final version for publication.

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