ASSESSING THE ECOLOGICAL FOOTPRINT OF ROAD TRANSPORT IN RAJSHAHI CITY: A PATH TOWARD SUSTAINABLE URBAN MOBILITY

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ABSTRACT

With the rapid pace of urbanization, Rajshahi City is being continuously confronted with environmental challenges, particularly due to pollution from its transportation sector. This study aims to measure the ecological footprint of Rajshahi city's road transport network and assess its environmental sustainability. Using emission factor models combined with detailed vehicle activity data and bio-capacity estimates derived from land use assessments, the research evaluates both the energy and physical footprints of the city's transport system. The study estimates Carbon Dioxide (CO_2) emissions from motorized vehicles using the average emission factor method and compares this against the city's bio-capacity. Major contributors to this footprint were buses, trucks, personal vehicles, and battery-run auto rickshaws. Results indicate a total transport footprint of 44,812.58 hectares, which significantly exceeds the city's available bio-capacity of 1,131.62 hectares, creating an ecological deficit nearly 40 times larger than the city's regenerative capacity. To address this imbalance, the study recommends sustainable measures such as promoting non-motorized transport (NMT), increasing urban greening, and adopting transit-oriented development (TOD). This paper offers valuable insights for policymakers to harmonize urban development with ecological sustainability in Rajshahi.

Keywords: *Ecological Footprint; Urban Transport; Environmental Sustainability; Emission Factors; Bio-Capacity.*

1. INTRODUCTION

Rapid urbanization across the globe, particularly in developing nations, has created unprecedented challenges for environmental sustainability. The transportation sector, a critical engine for urban economic activity, has emerged as a primary contributor to environmental degradation, responsible for significant greenhouse gas emissions, air pollution, and energy consumption (Ardila-Gomez et al., 2021; Dhakal & Schipper Lee, 2005). As Asian cities continue to expand, the escalating rate of motorization intensifies these pressures, posing serious risks to public health and ecological stability (Zegras & Birk, 1993). Consequently, achieving a balance between urban development and environmental preservation has become a paramount goal for policymakers and planners, necessitating a shift towards sustainable urban transport systems.

To effectively manage and mitigate the environmental impact of urban mobility, it is crucial to employ robust assessment tools. The ecological footprint has been recognized as a valuable and comprehensive metric for quantifying the environmental pressures of human activities, including transportation (Chi & Stone, 2005). By translating resource consumption and waste generation into the amount of biologically productive land and sea area required, the ecological footprint provides a clear indicator of sustainability. Studies in various urban contexts, from Merseyside to Dhaka, have utilized this approach to reveal that the transport footprint often exceeds a city's available bio-capacity, highlighting a significant ecological deficit and underscoring the urgency for sustainable transport strategies (Barrett & Scott, 2003; Labib et al., 2013).

While extensive research has focused on the transport-related environmental challenges in megacities, smaller and intermediate-sized cities undergoing rapid growth have received comparatively less attention. Cities like Rajshahi in Bangladesh are experiencing swift urbanization and motorization, leading to emerging environmental problems that mirror those of larger metropolises but within a different socio-economic and infrastructural context. An underdeveloped public transport system, a rising number of personal vehicles, and limited green spaces create a unique set of challenges that demand specific investigation to prevent the entrenchment of unsustainable development patterns.

This study, therefore, aims to address this research gap by measuring the ecological footprint of Rajshahi city's road transport network and assessing its environmental sustainability. By employing emission factor models combined with detailed vehicle activity data, this research quantifies the emissions of Carbon Dioxide (CO_2). The resulting ecological footprint is then compared against the city's estimated bio-capacity, derived from land use and green space assessments, to determine the extent of the ecological imbalance. The findings of this paper offer valuable, context-specific insights for policymakers to formulate and implement targeted strategies such as promoting non-motorized transport, expanding low-carbon public transit, and initiating urban greening projects to guide Rajshahi towards a more sustainable and ecologically resilient future.

2. METHODOLOGY

This section outlines the study area selected for analysis and describes the data collection methods used to acquire vehicle and land-use statistics necessary for the ecological footprint assessment.

2.1 Study Area and Methodology

The study area selected for CO_2 emission analysis is Rajshahi City Corporation (RCC), which covers an area of about 96.72 square kilometers. It is one of the major urban centers of Bangladesh, experiencing rapid urbanization and motorization in recent years. The city has a growing number of vehicles, industries, and commercial activities that significantly contribute to local carbon emissions. Due to its compact urban form and increasing transport demand, Rajshahi presents a critical case for assessing urban CO_2 emissions and their environmental impacts.

To estimate the transportation footprint of Rajshahi city's vehicles and road network, a similar methodology was followed. First, data on the total number of vehicles traveling in Rajshahi city from 2015 to 2025 was collected from the Bangladesh Road Transport Authority (BRTA). For the final computation of emissions, additional data was sourced from relevant research on vehicle fuel consumption and emissions specific to the Rajshahi region.

To apply the average emission factor method, CO_2 emission factors for various vehicle types and fuel types were collected. The total daily emissions for different vehicle groups were then estimated by multiplying the average emission factor by the total number of vehicles and their average daily activity. This daily emission value was then scaled up by multiplying it by the total days in a year to determine the overall tons of CO_2 emitted annually.
After calculating the total annual CO_2 emissions, the energy footprint of the roadway network was estimated. This was done by determining the area of forest land required to sequester the carbon emissions produced by the network's travel over one year, using a carbon sequestration factor from a reliable source like the EPA. This process yielded the energy footprint associated with vehicle data and activity in Rajshahi.

For the road pavement footprint, the percentage of land area dedicated to the road network was obtained from the Detail Area Plan (DAP) for Rajshahi. This allowed for the calculation of the total land cover in Rajshahi city used for roads. Finally, by combining the energy footprint from vehicle activity with the road network footprint, the total transport footprint for Rajshahi was calculated.

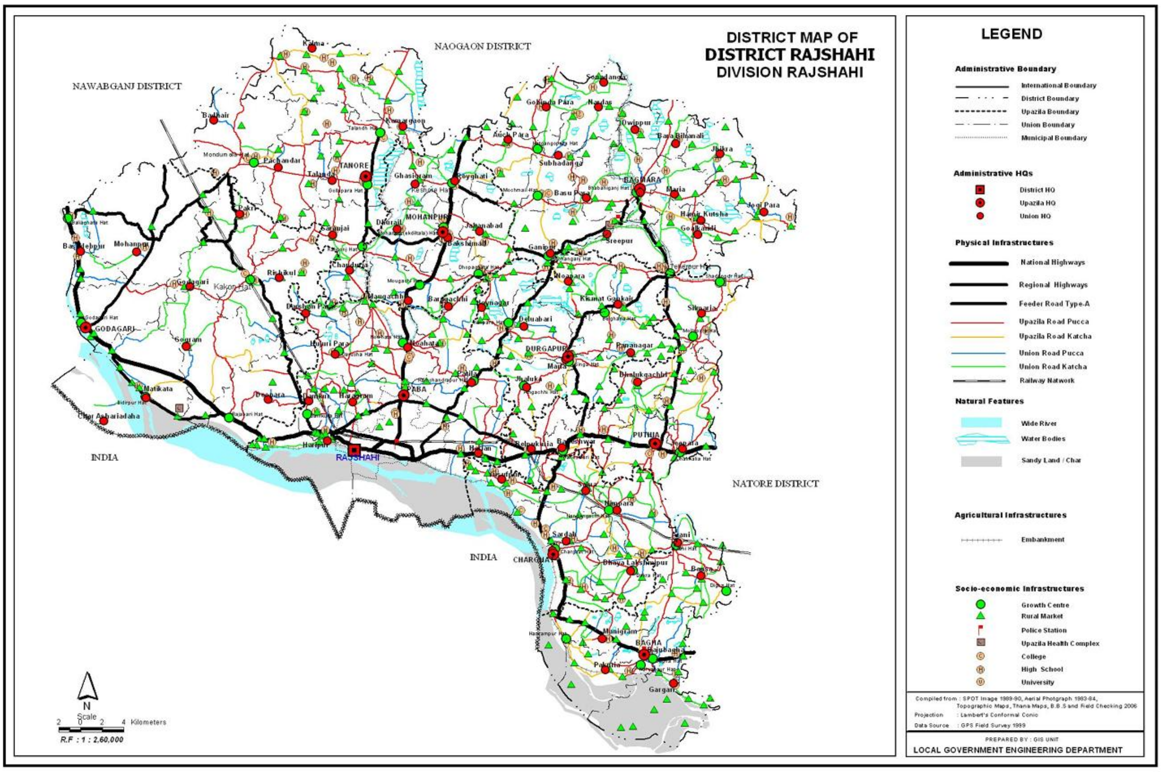

Figure 1: Map of road network in Rajshahi

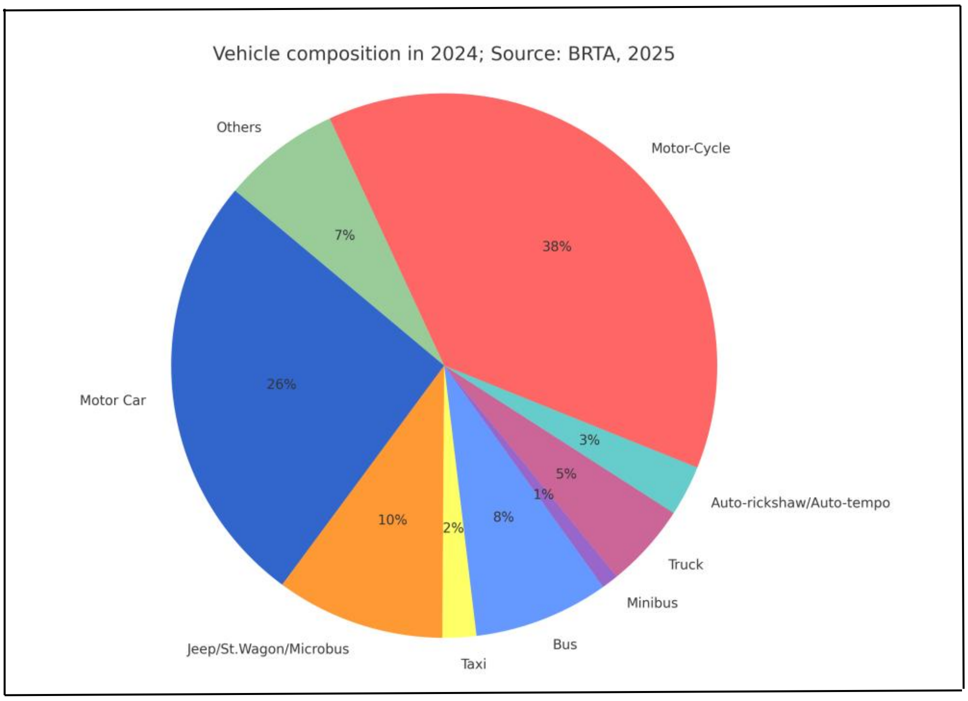

Figure 2: Vehicle composition in 2024; Source: BRTA, 2025

3. THEORIES AND CALCULATION

To accurately assess the environmental impact of Rajshahi's transport sector, specific theoretical frameworks and mathematical models were applied. The following subsections detail the definitions and formulas used to calculate the transport and ecological footprints.

3.1 Transport Footprint

Transport is one of the greatest contributions to Rajshahi's ecological impact. Motorized vehicles including auto tempo, buses, motorbikes, and autorickshaws have become much more common in the city, which has led to a huge increase in CO_2 emissions. A significant portion of the city's productive land is thought to be needed for sequestration of the overall carbon output from the transportation sector, based on vehicle activity statistics (average kilometers driven per day) and conventional emission factors. The increasing number of vehicles and dependence on fossil fuels are causing a transport-driven ecological burden, even though Rajshahi advocates greener initiatives than other urban centers. For this reason, sustainable mobility solutions like public transportation, non-motorized options, and low-emission vehicles are essential for minimizing the impact.

3.2 Ecological Footprint

Rapid urbanization, expanding transportation operations, and increased CO_2 emissions from motorized vehicles are the key factors influencing the city's ecological footprint. The need for biologically productive land to absorb emissions is growing more quickly than the city's ecological capability. Although Rajshahi is greener compared to other cities, the mismatch between resource use and available biocapacity implies a risk of ecological deficit. To keep things in balance, more green space must be added to cities, eco-friendly transportation must be encouraged, and land use planning must be sustainable.

3.3 Emission Factor model

A certain vehicle type and driving style are represented by a single emission factor. The following formula is used to estimate emissions:

E (p, k, m, t) = y (p, k, m, t) * v (p, k, m, t) * VKT (k, m, t)
E = emissions of pollutant (p), for vehicle class (k) and fuel type (m) during time interval (t)
y = emission factor for pollutant (p), for vehicle class (k) and fuel type (m) during time interval (t)
v = volume of vehicle class (k) differentiated by fuel type (m) at specific time interval (t), and VKT = Vehicle kilometer travel by vehicle class (k) for fuel type (m) at time interval (t).

4. RESULTS AND DISCUSSION

This section presents the quantitative findings derived from the emission factor models and land-use analysis. It details the estimation of energy and physical footprints, evaluates the city's current bio-capacity, and synthesizes these figures to determine the overall ecological sustainability of the transport sector in rajshahi.

4.1 Estimating Energy Footprints

For estimation of energy footprint, the amount of CO_2 emitted in Rajshahi from transport activity has been calculated using the emission factor model. The number of vehicles is determined based on the percentage of CNG and other fuel types for each vehicle class. These percentages are used on the base data of BRTA vehicle numbers. For the emission factors for different vehicle groups based on fuel type and emission factors are primarily focused on vehicles travel on Rajshahi's road network. The emission factors express emission from different vehicle types in gm/kilometer unit. The vehicle activity data from BRTA in Rajshahi expresses the average travel distance for specific vehicle groups in km/day unit.

Table 1: Vehicle CO_2 Emission From 20015-2025 For Rajshahi

Vehicle Types	**Vehicle type Percentage (%)**	**Fuel Types**	**No Of Vehicles**	**Vehicle Activity (KM/Day)**	**CO_2 Emission Factor (gm/KM)**	**Emission (Ton/Day)**
Pickup Cabin (Single)	0.024	Diesel	18	140	150	0.38
Water Tanker	0.00131	Diesel	1	120	2501	0.03
Pickup Cabin (Double)	0.014	Diesel	11	170	170	0.32
Small bus	0.00131	Diesel	1	200	200	0.04
Cargo Truck	0.00524	Diesel	4	200	300	0.24
Auto tempo	0.19	Petrol	148	120	150	2.66
Scooter	0.032	Octene	25	60	80	0.12
Motorcycle	99.69	Octene	75998	70	70	372.39
Hard Jeep	0.00787	Petrol	6	150	200	0.18
Micro Bus	0.031	Petrol	24	230	220	1.21
Ambulance	0.02	Petrol	16	90	200	0.28
Car (Saloon)	0.00262	Petrol	2	120	180	0.043
Tractor	0.01	Diesel	8	50	350	0.14
Auto Rickshaw	0.62	Petrol	480	110	120	6.33
Omni Bus	0.00393	Diesel	3	200	300	0.18
Tipper	0.00781	Diesel	6	140	300	0.25
Total (Ton/Day)			76751			384.79
		Year Average	**= 365*384.79**	**140449.45 Ton/ Year**		

Table 2: Total Area Needed for Absorbing CO_2 For Fuel

Total Tons of CO_2	**Sequestration (Tons CO_2/Acre/Year)**	**Hectares**
140449.45	1.6175	0.4047
Total area needed (in hectares)		35140.58

4.2 Estimating Physical Footprint

The entire road area of Rajshahi city, which is 96.72 sq. km (9672 hectares), is then used to calculate the total physical footprint or road network, which comes out to be 9672 hectares.

4.3 Bio-Capacity of Rajshahi City

The Total Rajshahi city is about 96.72 square km. It is estimated that about 11.7% of the Rajshahi city area is dedicated to open space which is about 1131.62 hectares of land.

4.4 Total Transport Footprint

The entire Transport footprint is just the function of the total energy footprint and the physical footprint of the road network system. It is the sum of these two components. By totaling them transportation footprint is 35140.58 hectares.

Table 3: Total Transport Footprint

Total Energy Footprint	35140.58 Hectares
Total Physical Footprint	9672 Hectares
Total Transport Footprint	44812.58 Hectares

4.5 Discussion of Ecological Deficit

Using an emission factor model, an analysis of Rajshahi's road transport emissions showed a notable and consistent rise in CO_2 output from 2015 to 2025, mainly from trucks and buses, despite having a smaller fleet, because of their high fuel consumption and long travel distances, followed by auto-tempos and private vehicles. The entire transport footprint, which represents the total land area needed to support the city's transport system, was 44,812.58 hectares when the physical footprint of Rajshahi's road network (96.72 km^2 or 9,672 hectares) was added.

Importantly, this footprint significantly outstripped Rajshahi's biocapacity, which was just 11.7% of the city's total size (1,131.62 hectares of open/green space). This resulted in an ecological deficit where the city's biological regenerative capacity was outpaced by transportation demands by about 39.6 times or 40 times.

It is evident that the current ecosystem of Rajshahi is insufficient to absorb the CO_2 produced by its transportation sector. This deficit highlights the unsustainable trajectory of the city's mobility patterns, mirroring issues seen in megacities like Dhaka but exacerbated by Rajshahi's intermediate size and limited public transport infrastructure. To mitigate this crisis, it is imperative to implement transformative strategies, including the expansion of non-motorized transport (NMT) infrastructure, increasing urban greening, and adopting transit-oriented development (TOD). Without immediate intervention to balance environmental preservation with urban growth, Rajshahi risks solidifying unsustainable development patterns.

5. CONCLUSIONS

This study assessed the ecological footprint of Rajshahi City's Road transport system and revealed a significant ecological deficit. The total transport footprint was calculated at 44,812.58 hectares, which is nearly 40 times higher than the city's available bio-capacity of 1,131.62 hectares. High emissions from buses, trucks, auto-tempos, and private vehicles, combined with limited green spaces and an underdeveloped public transport system, are placing tremendous pressure on the city's environment.

To move toward sustainability, Rajshahi must adopt integrated strategies such as promoting non-motorized transport, low-carbon and electrified public transit, urban greening projects, and freight management policies. Moreover, land-use planning and transport demand management should be prioritized to balance mobility needs with ecological preservation.

The methodology used to combine emission factor modeling with bio-capacity assessment offers a replicable framework for other rapidly urbanizing regions facing similar challenges. Without timely intervention, Rajshahi risks entrenching unsustainable development patterns; however, with proactive planning and sustainable transport initiatives, the city can steer toward a more ecologically resilient and livable future.

DECLARATION OF USE OF AI

The authors maintain full responsibility for the intellectual integrity of this work, including research concept, methodology design, data collection, analysis, analysis, result interpretation, and conclusion formulation.

Artificial Intelligence (AI) was utilized in a strictly limited capacity for language refinement. The role of AI was confined to correcting typographical errors and enhancing the textual coherence of the draft. No research findings or scientific arguments were derived or generated by AI tools.

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