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Research Article

Geospatial Analysis of Freight Transportation and Related Emissions: A Case Study in Java Island

Muhammad Ahlan[1,*], Ika Arfita[2], M. Rayan Zishan[3] , Sri Anggina Harahap[4]

[1]Department of Civil Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia
[2]Department of Obstetrics and Gynecology, Faculty of Medicine, Universitas Syiah Kuala, Banda Aceh, Indonesia
[3]Department of Informatics, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Banda Aceh, Indonesia
[4]Department of Geography and Planning, Faculty of Arts and Science, University of Toronto, Canada

*Corresponding author: Muhammad Ahlan (ahlan.sektim@usk.ac.id)

Abstract

The application of geospatial data in transportation planning continues to expand. Geospatial data is typically utilized through software that requires the data to be well-organized and broadly accessible. The application of geospatial data in the transportation sector presents significant challenges in regions having limited data. Java Island is one of the most densely populated islands in the world. Consequently, the volume of freight transportation in the island is also high. However, freight transportation data for Java Island is not stored in a comprehensive data repository. The objectives of this study are sixfold. First, identifying province level data regarding rice commodity surpluses and deficits. Second, collecting data on rice surpluses and deficits at the regency/municipality level. Third, developing the spatial map of the road network on the island of Java. Fourth, creating spatial maps of rice surpluses and deficits for each regency/municipality. Fifth, estimating rice distribution patterns. Sixth, estimating CO_2 emissions for rice transportation using toll roads and national roads. The analysis identified the spatial patterns of rice distribution and estimated the volume of rice transported along the main interprovincial freight corridor on Java Island. Furthermore, the study estimated the CO_2 emissions associated with the rice transportation flows identified in the previous step. The use of toll road infrastructure could reduce annual CO_2 emissions from rice transportation between Jakarta and East Java by up to 11,772.5 tonnes. The commodity distribution pattern identified through geospatial analysis is largely consistent with that identified through field surveys conducted in a previous study. The findings demonstrate that geospatial analysis can effectively estimate freight distribution patterns. It can also preliminarily estimate CO_2 emissions and their changes resulting from transportation route and infrastructure modifications. Therefore, geospatial analysis can serve as an effective preliminary approach, in conjunction with field surveys or other transportation modelling techniques, for planning sustainable transportation infrastructure.

Keywords: Geospatial; Freight; Transportation; Emission; Java.

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Introduction

Geospatial data has been widely employed in sustainable freight transportation research. A previous study combined the concepts of shared logistics and freight pooling within a geospatial data–driven framework. The study successfully proposed a transportation scheme that has the potential to reduce emissions by approximately 20% [1]. Kawasaki et al. [2] employed geospatial analysis to examine the effects of incentive and carbon credit trading policies on freight transportation mode shifts. In their study, Kawasaki et al. utilized transportation data generated through the expansion of survey data published by the Japanese government. The study provides technical recommendations that can be used to enhance the shift in freight transportation modes. Such modal shifts have the potential to reduce CO_2 emissions. Brusselaers et al. [3] estimated transportation activities related to construction work. The study used geospatial analysis. The study estimated the amount of CO_2 generated from transportation activities associated with the construction work.

The studies mentioned above utilized transportation databases to conduct geospatial analyses of freight transport. The findings from these studies can serve as valuable inputs for reducing CO_2 emissions generated by freight transportation activities.

However, a database that provides origin–destination points for freight transportation on the island of Java is not publicly available [4-6]. The available datasets are non-transportation databases that present information on commodity surpluses and deficits [7]. Such non-transportation data should be leveraged to estimate freight transportation activities and the resulting CO_2 emissions.

The objectives of this study are sixfold. First, identifying province level data regarding rice commodity surpluses and deficits. Second, collecting data on rice surpluses and deficits at the regency/municipality level. Third, developing the spatial map of the road network on the island of Java. Fourth, creating spatial maps of rice surpluses and deficits for each regency/municipality. Fifth, estimating rice distribution. Sixth, estimating CO_2 emissions for rice transportation using toll roads and national roads. This study is expected to contribute to the advancement of sustainable development. In addition, this study is expected to support the concepts and strategies of sustainability-oriented development [8-12].

Materials and Methods

This study was conducted through several steps. First, the provinces on the island of Java that have rice commodity surpluses and deficits were identified through a literature review. Second, data on rice surpluses and deficits at the regency/municipality level were collected. Third, the spatial map of the road network on the island of Java was developed. Fourth, spatial maps of rice surpluses and deficits for each regency/municipality were created. Fifth, rice distribution was estimated. Sixth, CO_2 emissions were estimated for rice transportation using toll roads and national roads.

Rice was selected in this study because it is one of the commodities that have the highest transportation volume on the island of Java [13]. Rice surplus and deficit data were obtained from the Central Statistics Agency of the Republic of Indonesia [7]. Geospatial software was used to create a spatial map of the road network. The development of this spatial map referred to several separate road infrastructure maps provided by the Indonesian government. The spatial maps of rice surpluses and deficits were created using geospatial software. The rice distribution was estimated based on the locations of regencies and municipalities having rice deficits and surpluses. $CO2$ emissions was estimated based on the previous study [14].

Spatial analysis is a quantitative approach used to study spatial phenomena in geography and earth sciences. Its primary function is to transform spatial data into various representations and to extract meaningful information and knowledge from it [15]. Previous studies shows that geospatial analysis and GIS are widely used to estimate transportation flows and CO_2 emissions by constructing spatially explicit emission inventories, allocating freight movements across networks, and analyzing spatial emission patterns at various geographic scales [16], [17], [18], [19]. In this study, the spatial maps of rice surpluses and deficits were created using geospatial software. In simple terms, the surplus and deficit data of rice commodities were spatially allocated according to their respective locations. Based on these spatial maps, geospatial analysis was conducted by estimating the origins and destinations of freight transportation based on spatial proximity and their relationships with other origin and destination points.

CO_2 emissions were estimated based on the **Table 1** [14]. The data in Table 1 were derived from official certification data of new trucks in the European Union (based on VECTO—Vehicle Emission Calculation Tool) that collected during the 2019–2020 baseline reporting period through the EU monitoring system and subsequently processed to obtain average CO_2 emissions and fuel consumption per truck category. The VECTO dataset has been applied in several previous studies to estimate CO_2 emissions both within and outside the EU [20,21].

Table 1. CO2 emissions by vehicle sub group [14]

Vehicle sub group	CO2 emissions (gCO2/km)	Description
4-UD	814.1	Rigid, 4x2 axle, for urban delivery
4-RD	627.0	Rigid, 4x2 axle, for regional delivery
4-LH	786.4	Rigid, 4x2 axle, for long haul delivery
5-RD	861.7	Tractor, 4x2 axle, for regional delivery
5-LH	783.5	Tractor, 4x2 axle, for long haul delivery
9-RD	696.9	Rigid, 6x2 axle, for regional delivery
9-LH	873.3	Rigid, 6x2 axle, for long haul delivery
10-RD	854.1	Tractor, 6x2 axle, for regional delivery
10-LH	806.5	Tractor, 6x2 axle, for long haul delivery

CO_2 emissions were estimated based on Equation (1). CO_2 emissions are expressed as emissions per unit freight weight (grams per ton of freight). Distance refers to the travel distance (km), while payload denotes the load weight per vehicle (ton). Payload was estimated based on previous studies [4].

$$CO2\ emissions = CO2\ emissions\ per\ vehicle\ x\ distance\ x\ \frac{1}{payload} \quad (1)$$

Results

Rice surplus and deficit data is shown in **Table 2**. East Java Province was selected as the source of rice surplus and deficit data because it is the highest rice-producing province in Indonesia [22]. Based on the information, the regencies/municipalities recording the largest rice surpluses are Lamongan (421,850.5 tonnes/year), Ngawi (420,455.9 tonnes/year), Bojonegoro (327,929.6 tonnes/year), Madiun (206,636.3 tonnes/year), and Tuban (205,910.1 tonnes/year). Conversely, the largest rice deficits were recorded in Surabaya City (−204,396.0 tonnes/year), Malang City (−56,741.2 tonnes/year), Sidoarjo Regency (−45,681.4 tonnes/year), Malang Regency (−32,484.7 tonnes/year), and Kediri City (−15,076.8 tonnes/year)

Table 2. Rice surplus and deficit in East Java

No	District/City	Surplus/deficit (tonnes/year)
1.	Bangkalan	46,930.3
2.	Banyuwangi	153,151.8
3.	Blitar	28,664.4
4.	Bojonegoro	327,929.6
5.	Bondowoso	93,444.9
6.	Gresik	137,914.0
7.	Jember	160,628.3
8.	Jombang	105,133.3
9.	Kediri	9,427.0
10.	Kota Batu	-12,320.4
11.	Kota Blitar	-7,329.1
12.	Kota Kediri	-15,076.8
13.	Kota Madiun	-4,157.7
14.	Kota Malang	-56,741.2
15.	Kota Mojokerto	-6,885.3
16.	Kota Pasuruan	-8,824.8
17.	Kota Probolinggo	-13,021.8
18.	Kota Surabaya	-204,396.0
19.	Lamongan	421,850.5
20.	Lumajang	91,234.7
21.	Madiun	206,636.3
22.	Magetan	131,507.7
23.	Malang	-32,484.7
24.	Mojokerto	97,872.5
25.	Nganjuk	174,315.1
26.	Ngawi	420,455.9
27.	Pacitan	7,890.2
28.	Pamekasan	-5,984.6
29.	Pasuruan	37,952.5
30.	Ponorogo	153,268.5
31.	Probolinggo	25,412.2
32.	Sampang	38,336.3
33.	Sidoarjo	-45,681.4
34.	Situbondo	42,118.9
35.	Sumenep	52,305.2
36.	Trenggalek	11,693.6
37.	Tuban	205,910.1
38.	Tulungagung	47,510.6

The spatial map of the road network in Java Island is shown in **Figure 1**. The map shows that the road infrastructure connects the East Java Province to other provinces—Banten, Jakarta, West Java, Central Java, and Yogyakarta—in Java Island. As a result, the rice surplus can be distributed to other provinces in Java Island via road transportation. Based on the figure, the road transportation infrastructure in Java Island is divided into two categories: the national road network and the toll road network.

The geospatial map of rice surplus and deficit in East Java Province is shown in **Figure 2**. Regencies/municipalities with very high rice surpluses are concentrated in the north-western and northern parts of East Java Province, particularly Ngawi Regency, Bojonegoro Regency, and

Lamongan Regency. Regencies/municipalities with lower rice surpluses are distributed across most areas of East Java. The municipality with the largest rice deficit is Surabaya City. Areas with lower rice deficits are located in the vicinity of Surabaya City, around Malang City, and in Pamekasan Regency on Madura Island.

Figure 1. Transportation network in Java Island (Source: author)

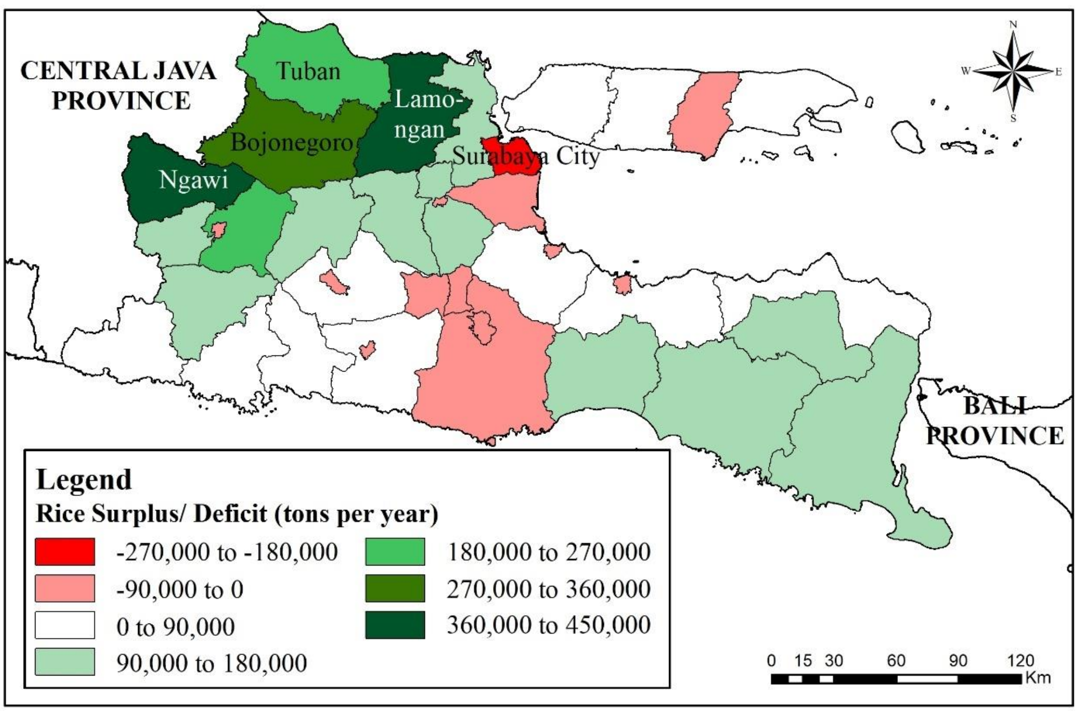

Figure 2. Geospatial map of rice surpluses and deficits in East Java Province (Source: author)

The rice distribution patterns can be estimated based on the geospatial map of rice surpluses and deficits. Rice surpluses from Ngawi Regency and Bojonegoro Regency, which are located in the western part of the province, are likely to be transported to provinces situated west of East Java, such as Jakarta, West Java, and Banten. This is due to the relatively close proximity of these surplus-producing regions to those provinces. Rice surpluses generated in areas surrounding Surabaya City are likely to be distributed to Surabaya and its surrounding areas because of the short distance between the surplus-producing regions and the city. Similarly, rice surpluses from areas around Malang City are expected to be transported to Malang and neighboring areas because of their geographical proximity.

Meanwhile, rice surpluses produced in regencies and municipalities located in the eastern part of East Java are expected to be distributed to provinces situated to the east and north of East Java. This distribution pattern is influenced by the relatively close distance between these surplus-producing areas and the neighboring provinces located in those directions.

The comparison between geospatial analysis results and field survey results is presented in **Table 3**. The field survey results are obtained from previous study [4]. The table shows that the rice commodity distribution pattern along the main interprovincial corridor in Java Island is broadly similar between the geospatial analysis and field survey results. However, there are considerable differences in the estimated freight quantities between the two approaches.

Table 3. Comparison between geospatial analysis results and field survey results

Method	Origin−destination (transportation pattern)	Total freight weight (tonnes/year)
Geospatial analysis	Ngawi–Jakarta	Maximum 121,000
Field survey	Ngawi–Jakarta	Maximum 748,385.5

The CO_2 emissions generated by rice transportation in Java Island is presented in **Table 4**. The Ngawi–Jakarta corridor is selected based on the result of geospatial analysis. The CO_2 emissions generated by two-axle trucks operating on toll roads are estimated at 95,626.2 g per tonne of rice transported. Two-axle trucks operating on national roads generate 99,086.4 g CO_2 per tonne of rice transported. Multi-axle trucks operating on toll roads generate only 19,614.08 g CO_2 per tonne of rice transported. The use of toll roads for rice transportation can reduce CO_2 emissions by a maximum of 80.2%.

Table 4. Estimated CO_2 Emissions of Rice Transportation in the East Java–Jakarta Corridor

Vehicle sub group	CO_2 emissions (gCO_2/km)	Corridor distance (km)	Payload (tonnes/vehicle)	CO_2 emissions (g/tonnes freight)	Corridor type
4-LH	786.4	608	5	95,626.2	Toll road
4-LH	786.4	630	5	99,086.4	National road
10-LH	806.5	608	25	19,614.08	Toll road

Discussion

This study utilizes limited data to assess the impact of transportation infrastructure availability on CO_2 emissions. Geospatial analysis can be used to identify commodity distribution patterns and preliminarily estimate changes in CO_2 emissions associated with modifications to transportation routes or infrastructure. The commodity distribution patterns identified through geospatial analysis in this study are generally consistent with those identified via field survey in a previous study [4]. Both this study and previous research indicate that Ngawi Regency and its surrounding areas constitute the origin of rice commodities transported to the western region of Java Island, particularly Jakarta. These findings indicate that the commodity distribution patterns derived from geospatial analysis can closely approximate those obtained from field surveys. However, the estimated quantities of commodity distribution differ between the two studies. Therefore, geospatial analysis can serve as a preliminary source of information to guide subsequent field surveys for determining commodity distribution patterns and quantities.

The results indicate that the use of toll roads can reduce CO_2 emissions from rice transportation by a maximum of 80.2%. Therefore, the development of toll road infrastructure along major trade corridors may be considered as a strategy for reducing freight transportation emissions. Similarly, the expansion of environmentally friendly transportation modes, such as railways, along key trade corridors should also be considered to further reduce CO_2 emissions from freight transportation. The analysis reveals a potential rice transportation volume of up to 748,385.5 tonnes per year along Ngawi–Jakarta corridor. Consequently, the use of toll road infrastructure could reduce CO_2 emissions from rice transportation by as much as 11,772.5 tonnes annually.

The finding of this study is consistent with the previous research [23]. Previous studies have found that freight transportation using higher-capacity trucks results in lower CO_2 emissions compared to transportation using lower-capacity trucks. The differences in CO_2 emission intensity among vehicles with different payload capacities are attributed to economies of scale. Economies of scale occur when output increases faster than production costs. As a result, the cost per unit decreases as the scale of production grows [24].

Several limitations should be noted. First, the study does not explicitly consider the road infrastructure connecting origins and destinations to the toll road network. Since 10-LH trucks have high gross vehicle weights and are primarily suitable for toll roads, additional infrastructure development or multi-stage distribution systems involving smaller trucks and warehousing facilities may be required. Second, the analysis does not account for round-trip freight movements. Freight transportation generally consists of outbound and return trips, and incorporating both directions may affect the estimated emissions.

Nevertheless, the findings demonstrate that geospatial analysis can effectively estimate freight distribution patterns and provide preliminary estimates of the associated changes in CO_2 emissions resulting from transportation route and infrastructure modifications. Therefore, geospatial analysis can serve as a valuable preliminary tool for planning and prioritizing sustainable transportation infrastructure development, with its findings to be further refined through field surveys or more detailed modelling.

Conclusion

The study demonstrates the potential of geospatial analysis to characterize freight distribution patterns and preliminarily quantify CO_2 emission changes resulting from transportation network and infrastructure interventions. As such, geospatial analysis can contribute to informed decision-making in the development of sustainable transportation systems. As such, geospatial analysis can contribute to informed decision-making in the development of sustainable transportation systems.

Based on the comparison between this study and previous research, geospatial analysis produces freight transport patterns that are generally similar to those obtained from field surveys. Therefore, spatial analysis can be used as a preliminary analytical approach, which can subsequently be complemented by field surveys for more accurate determination of commodity distribution patterns. In general, spatial analysis is more efficient in terms of resource requirements compared to field surveys. As a result, geospatial analysis can be used to simulate the impacts of planning or design interventions on CO_2 emission changes. The results of spatial analysis can then be further validated or refined through field surveys or other modelling approaches that typically require more resources than geospatial analysis methods.

To date, geospatial analysis has generally been conducted using comprehensive and large-scale datasets. The application of geospatial analysis based on limited data, particularly for sustainable transportation infrastructure planning, remains relatively scarce. This study presents a geospatial analysis using a relatively limited dataset and demonstrates that, despite data constraints, such an approach can effectively capture the potential patterns of freight distribution.

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Conflict of Interest

The authors declare no conflicts of interest in this research.

Author Contribution Statement

Muhammad Ahlan: Conceptualization, Methodology, Writing – Original draft, Writing – review & editing. **Ika Arfita:** Validation, Resources. **M. Rayan Zishan:** Visualization. **Sri Anggina Harahap:** Conceptualization.

Data Availability Statement

The data used to support the findings of this study are included within the article.

Ethics Approval

Ethics approval is not required.

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