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RESEARCH ARTICLE

Contribution of Commuters and Transit Activities on The Road Transport Carbondioxides Emission in Surakarta

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Abstract Road transportation is the main contributor to emissions in Surakarta City, Indonesia. Massive commuting and transit activities are predicted as the driving forces behind this condition. This research took place in the administrative area of Surakarta from July–August 2022. It aimed to determine the impact of commuting and transit activities on the amount of carbon dioxide (CO_2) emitted by the city's road transportation and develop a spatial interpretation of the emission distribution. A Tier 3 approach was used to estimate the emissions from average daily traffic data based on a 24-hour count and the characteristics of the monitored road segments with the Mobilev software. Results showed an estimated emission of 722,795.3 tonnes CO_2e/year from road transportation. Commuting and transit accounted for 50.33% of the city's total road emissions or 133.77% of local vehicle emissions according to calculations from fuel sales, which were dominantly produced by private passenger cars (38.26%) and motorcycles (37.71%). The spatial distribution indicated a pattern where emission loads were higher at city gates and along transit lines than in the central business district (CBD) area.

1. Introduction

Anthropogenic emissions have long been assumed to be the main driver of climate change (Shuai et al., 2017), particularly due to the use of and dependence on fossil fuels (Henderson et al., 2018) and the climate system feedbacks on emitted greenhouse gases (Anderson et al., 2016). The 2020 World Meteorological Organization report shows that CO_2 in the atmosphere reached its highest concentration of 407.8 ± 0.1 ppm in 2018, which directly leads to the increasing severity and frequency of climate change impacts, such as sea level rise (Das and Mangwani, 2015), acidification (Nikinmaa, 2013), hydrometeorological disasters (Intergovernmental Panel on Climate Change (IPCC), 2014), and threats to biodiversity that may result in extinctions (Bellard et al., 2012).

The Fifth Assessment Report (AR 5) document states that transportation is one of the leading contributors to greenhouse gas emissions (IPCC, 2015). This sector comprises 14% of direct emissions and 0.3% of indirect emissions globally. These figures are projected to multiply as mobility increases due to the growth of population size and demand (Hickman et al., 2010). Accessibility and transportation are considered the keys to successful development (Cheng et al., 2015). Development grows with urbanization, which is predicted to increase the urban population by up to 66% in 2050 (Xue, 2014). With more people being attracted to cities, alternative settlements are developed in nearby regions and create urban sprawl that lengthens their travel distance (Denant-Boemont et al., 2018).

In terms of location and function, Surakarta is a strategic urban area in Central Java, Indonesia. The city is traversed by a strategic interprovincial transit route (Nurdiani et al., 2019) and is one of Indonesia's main MICE (meetings, incentives, conventions, and exhibitions) destination cities. Also, it has an important role as the center of economic activities in the Greater Solo area because it has significant economic potential and a variety of adequate infrastructure (Setyono et al., 2020)—i.e., the two main factors attracting commuters from the hinterland (Obermayr, 2017). The Surakarta area is mostly designated for urban purposes, making it vulnerable to high emission loads, especially in signalized intersection areas (Gulia et al., 2014) and economic centers (Fan et al., 2017). In addition, with the potentially increasing traffic of commuters in the city, mobility on commuter and transit lines is predicted to add to transport emission loads and put more pressure on air quality (Himawan and Nancy, 2022).

According to the city's greenhouse gas (GHG) inventory, the emission load was projected to reach 3.27 million tonnes of CO_2 equivalent (CO_2e)/year in 2021 (Himawan and Nancy, 2022). Excluding electricity generation, this number would be around 652,028.31 tonnes CO_2e/year. Energy consumption is the main contributor to Surakarta's GHG (66%), and the transportation sector releases 72% of total emissions from energy consumption. This makes road transportation a key category of GHG producers in Surakarta (Setyono et al., 2020), which showed an increasing trend from 2017 to 2021.

The GHG inventory is, however, considered less indicative of the actual problem of transportation emissions in Surakarta. Limited data availability on fuel sales (top-down approach) does not match the character of the city's administrative area, thus existing estimates of emissions remain less comprehensive and do specifically represent those from commuters and transit lines. Mobility on these lines is predicted to have a significant contribution to emissions in Surakarta, even though most fuel transactions are conducted outside the city. In addition, the top-down estimation approach does not show the emission distribution in detail, which can otherwise be useful for emission control planning.

This research is expected to reduce uncertainties in the estimation of transport emissions that can be associated with the effects of the top-down approach due to the city's character. It aimed to determine the effects of commuting and transit on transport emissions in Surakarta. The mechanism used in the estimation was a bottom-up approach that calculated the average daily traffic (ADT) for five categories of vehicles (motorcycles, passenger cars, light-duty vehicles, heavy-duty vehicles, and buses) based on a 24-hour count. Calculations were performed on a Tier 3 basis using Mobilev 3.0 software, and the results were displayed on a map showing the distribution of transport emissions in Surakarta.

2. Methods

Research Location and Period

This research took place within the administrative borders of the City of Surakarta (Figure 1), covering an area of 46.72 km^2 (BPS-Statistics of Surakarta Municipality, 2022). The average daily traffic (ADT) data was collected from July to August 2022 which was calculated as road transport carbon dioxide equivalent (CO_2e) emission. Commuter trend analyses used secondary data on ADT every December at the period of 2019 to 2022

Data and Tools

The tools used in this study included closed circuit televisions (CCTVs), manual tally counters, Google form sheets for ADT collection, and laptops/computers equipped with ArcGIS Pro, Mobilev 8.0, and SPSS 26 programs. The research materials were the most recent base maps of Surakarta, CCTV footage at 57 road segments, and secondary data on ADT at city gates for the 2019–2022 period.

Data Collection

To estimate emissions, data on road characteristics and ADTs were inputted into the Mobilev 3.0 software for Tier 3 calculations. Details of road characteristics (road length, direction, number of lanes, location, slope, and status) were observed directly in the field. To obtain ADTs, the number of passing vehicles was first tallied for 24 hours using a bottom-up approach from the CCTV footage of 57 roads in the administrative area of Surakarta from July to August 2022. Then, the tally counts were averaged according to the selected modes of transportation: motorcycles (MC), passenger cars (PC), light-duty vehicles (LDV), heavy-duty vehicles (HDV), and buses. To complement this information, secondary data on ADTs were also collected at city gates on seven road segments, including Jl. Yos Sudarso, Jl. Slamet Riyadi Kleco, Jl. Dr. Rajiman Makam Haji, Jl. Adi Sucipto Jajar, Jl. Ir. Sutami, Jl. Adi Sumarmo Klodran, and the ring road. The data was used as baseline analysis on the commuter trend in Surakarta. These data were obtained every December for the 2019–2022 period from the CCTV footage of the Transportation Services of Surakarta City, with three modes of transportation: motorcycles, cars, and heavy-duty vehicles.

Data Analysis

Emission estimation on major road segments

The road segment in this study is divided into two categories: major roads and minor roads. Major road refers to

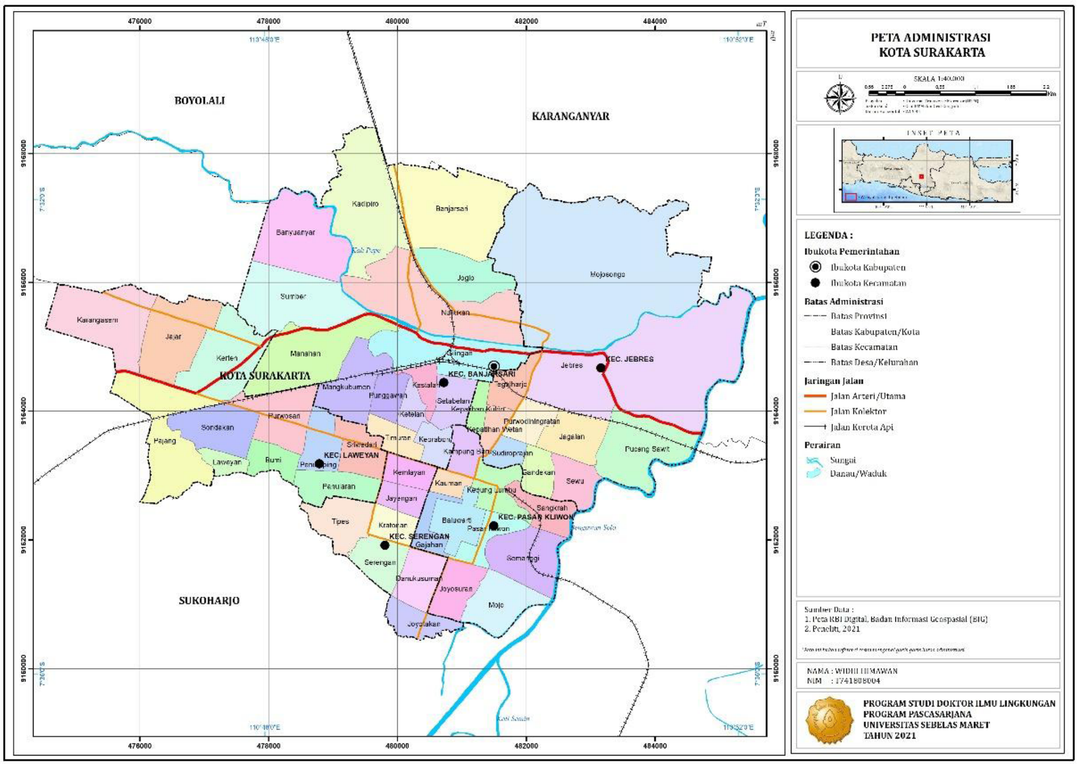

Figure 1. Administrative area of Surakarta City

a segment monitored by CCTV allowing for direct calculation of ADT from the footage. Emissions (*E*) were estimated for 57 major road segments with a total length of 75.63 km or around 30.78% of the entire road length in Surakarta. The estimation was calculated in Mobilev using the basic IPCC formula below:

$$\mathbf{E = AD \times EF}$$

E : Estimation of emissions in a certain time unit (tonnesCO_2e/year)
AD : Activity data (units adjusted)
EF : Emission factor (unit adjusts)
(IPCC, 2006; EMEP EEA Corinair 2013)

In Mobilev 3.0, the formula was modified to include two more variables: vehicle kilometers traveled (VKT) and changes in emission control technology, which were calculated using the equations below:

$$\mathbf{VKT_{j,\,line} = \sum_{i=1}^{n} Q_{ji} I_i}$$

$VKT_{j\ line}$: *Vehicle kilometers traveled* j on road I which is calculated as the source line (km/year)
Q : The volume of vehicles passing in category j on the road i is calculated as units (vehicles/year)
I_i : Length of road I (km)

$$\mathbf{E_{cji} = VKT_{ji} \times EF_{cj}\,(100 - C)/100}$$

E_{cji} : Pollutant emission c for category j vehicles on road i
VKT_{ji} : *Vehicle kilometers traveled* j on road i which is calculated as the source line (km/year)
EF_{cj} : Emission factor c for category j vehicles
C : Efficiency of emission control technology in vehicles, C can be worth 0 if emission control technology is not installed

(Suhadi et.al., 2014)

A Tier 3 approach was used in the calculation, resulting in smaller uncertainties (i.e., higher accuracy). The calculated emission is expressed as tons CO_2e/year.

Emission estimation on minor road segments

The length of the minor roads was calculated using the average vehicle kilometers traveled for each road class (*a*) that was monitored by CCTV ($VKT_{a(n)}$). This value was then combined with the length of the unmonitored road in each class to estimate fuel consumption ($FC_{as(n)}$). This assumed fuel consumption is the activity data used to calculate emissions per vehicle category for each road class.

$$\mathbf{E_{mr} : \frac{VKT_{a(n)} \times FC_{as(n)} \times EF_{(n)}}{10^6}}$$

Mr : Minor road emissions (tonCO2 / year)
$VKT_a(n)$: Vehicle kilometres travelled on road class a and vehicle mode n
$FC_{as(n)}$: Vehicle mode fuel consumption assumption n (g/km)
$EF_{(n)}$: Vehicle mode emission factor n (kg/kg)

Spatial interpretation of emissions

To interpret the spatial distribution of CO_2 emissions from transportation, a grid measuring 500 m x 500 m was used. The CO_2 emission was divided into major roads and minor roads. Emissions on minor roads were further grouped according to the proportion of the road length unmonitored by CCTV on each grid.

3. Result and Discussion

The basis for estimation in this research is the emission inventory. Emissions inventories provide official data on the amount of emissions released into the atmosphere at different sources and at certain periods (Gioli et al., 2015). The emission inventory is used as a basis for air quality modeling to the potential emissions of each activity, the distribution of emissions, and the identification of potential emission reduction measures (Shahbazi et al., 2016).

Road transportation in Surakarta in 2022 produces 722,795.3 tonnes CO_2e/year consisting of 173,135.97 tonnes CO_2e/year from major roads and 549,659.3 tonCO2 /year from minor roads. Based on category, private vehicles are the main contributors to CO_2 emissions, with motorcycles and passenger cars accounting for 52.66% and 33.13% of the total transport emissions. On CCTV-monitored major roads, passenger cars (40.32%) produced slightly higher CO_2 emissions than motorcycles (39.68%). Contribution on CO_2e emission from each category of the vehicle has a different pattern than in 2014. People tend to use passenger cars rather than motorcycles which are more inefficient on load factor. The tendency to switch to passenger cars is following Holz-Rau and Scheiner (2019) research on modern people's views on vehicle modes as a solution to the mobility limitations of urban areas. These results indicated that private modes of transportation remain the vehicle of choice for people's mobility in Surakarta.

Improved economic conditions, ease of ownership application, and convenience while traveling are the determining factors of the increased use of private vehicles for medium-distance mobility. The growth of passenger cars, however, increases fuel consumption and adds to the emission loads generated by the transportation sector. Passenger cars have worse fuel economies than motorcycles. In 2015, the fuel economies of cars equipped with Euro 4 technology (current Indonesian standards) were 7.9-9 Lge/100 km (ASEAN Secretariat, 2019), while motorcycles were 1.94 Lge/100 km (Tuayharn et al, 2015). The emission has heavier pressure considering inefficiency on a load factor of passengers cars.

The distribution of transport emissions presented in Figure 1 shows a greater CO_2 accumulation at city gates and transit lines. This condition was observed on Jl. Yos Sudarso (south), Jl. Slamet Riyadi Kleco (west), Jl. Ir. Sutami (east), the ring road (the city gateway), and Jl. Ahmad Yani (transit line). Despite the term, the ring road in Surakarta is not "whole" in that it does not comprise a series of roads encircling the city but rather a road segment on the north that connects the national (cross-provincial) road to the Mojosongo intersection, from which point vehicles should pass through the city center to reach adjacent regions. From this pattern, it can be inferred that emissions accumulate differently across the city.

Surakarta is the center of activity for people from the hinterland areas and has strategically located transit routes with high-intensity commuting and transit activities. As a result, a greater amount of emission is released at city gateways and along the transit routes, which corresponds to the theory

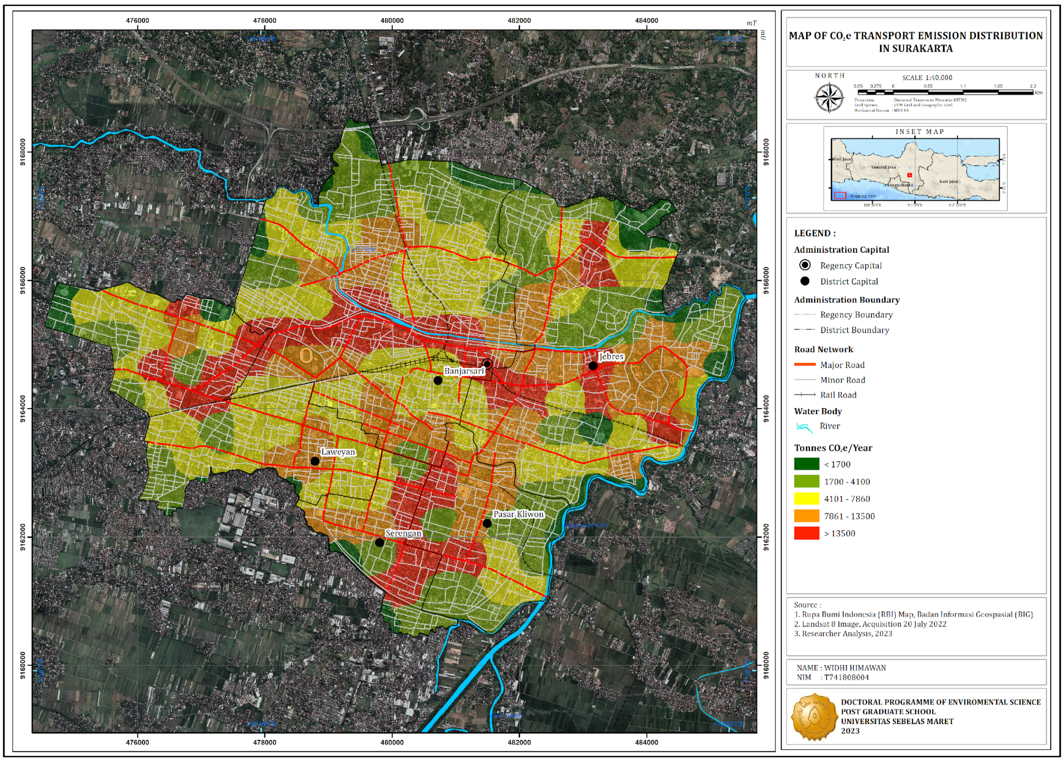

Figure 1. Distribution of carbon dioxides equivalent (CO2e) emission from transportation in Surakarta at 2022

that transport emissions accumulate at vital intersections (Gulia et al., 2014) and economic centers (Fan et al., 2017). In conclusion, commuting and transit contribute significantly to the transport emissions in Surakarta.

This study also compared total emissions and emissions generated at city gates and along transit lines on major roads. As seen in Figure 2, there are 18 segments representing the gateways and transit routes: Kyai Mojo Road (access from Bekonang, Sukoharjo), Makam Haji Street, Adi Sucipto Road (the segment in front of the House of the Regional Representatives), Slamet Riyadi Kleco Road, Adi Sumarmo Road (toll gate to the west of the city), Mangunsarkoro Street, Solo-Purwodadi Road, Sumpah Pemuda Street, Tangkuban Perahu Street, the northern ring road (the city's north entrance gate), Ir Sutami Street, Juanda Street (east entrance gate), Yos Sudarso Road, Kapten Mulyadi Street (south entrance gate), Veteran Street, Dr Soeharso Street, and Ahmad Yani Street (transit access point). The comparison results showed that commuter and transit lines contributed 87,145.38 tonnes of CO_2/year (50.33%) to total emissions on the monitored routes (major roads) and up to 133.77% of local vehicle emissions based on fuel sales data.

Local Transportation Agency states that the number of commuter vehicles during working hours is more than three times that of local vehicles. Surakarta does not have an outer ring road to divert transit vehicles. Transit vehicles pass through the Surakarta urban area on certain roadways including Ahmad Yani Street. Surakarta City acts as the economic and service center for the Greater Solo region. This condition, according to Obermayr (2017), raises the problem of temporary commuting, especially due to the imbalance of development in the hinterland area.

Yos Sudarso Road produced 12,377.32 tonnes of CO_2e/year, which is the highest CO_2 concentration among all monitored segments and the second-highest emission per kilometer. This confirmed that commuters' activity has a significant impact on the city's emission load. Yos Sudarso Road is the main entrance point for commuters from the south of Surakarta (Sukoharjo and Wonogiri). Based on the highest emission released, it can be said that commuters mainly come from the southern hinterland areas. The second-highest CO_2 concentration, 11,696.4 tonnes CO_2/year, was generated by mobility on Ahmad Yani Street. This road is the main transit access point linked to the Central Bus Station Tirtonadi and is thus used mainly by intercity heavy-duty vehicles.

A 24-hour observation found that commuting and transit activities had different traffic patterns. Commuter roads (gateways) had the greatest traffic volume in morning rush hour times (6:00–7:00 a.m.), mainly comprising of private vehicles (motorcycles and passenger cars), followed by a high ADT range until 4:00 p.m. This average daily traffic (ADT) pattern, especially the peak volume, corresponds to Li et al. (2022), which found that ADT tended to be the highest in the morning. Meanwhile, compared to other lines, the transit lines showed a different pattern in the number and time of peaks and the maximum ADT range. ADT peaked from 8:00–9:00 a.m. and in the afternoon from 4:00–5:00 p.m. Also, a maximum ADT range with several peaks between 8:00 a.m. and 5:00 pm. was identified, which is likely influenced by bus arrival and departure schedules that increase the number of private vehicles picking up and dropping passengers at the stations. In addition, goods-transporting light-duty vehicles (LDVs) mainly pass Ahmad Yani Street and comprise the majority of modes on this road segment.

Carbon dioxide emissions at the city gateways and on transit lines were primarily generated by private vehicles (motorcycles and passenger cars). The highest emission contributor was passenger cars, 38.26%, which was slightly higher than motorcycles, 37.71%. Carbon dioxide emission from buses was the lowest, indicating commuters' low interest in using public transportation. Economic improvement in areas surrounding Surakarta allows commuters to seek

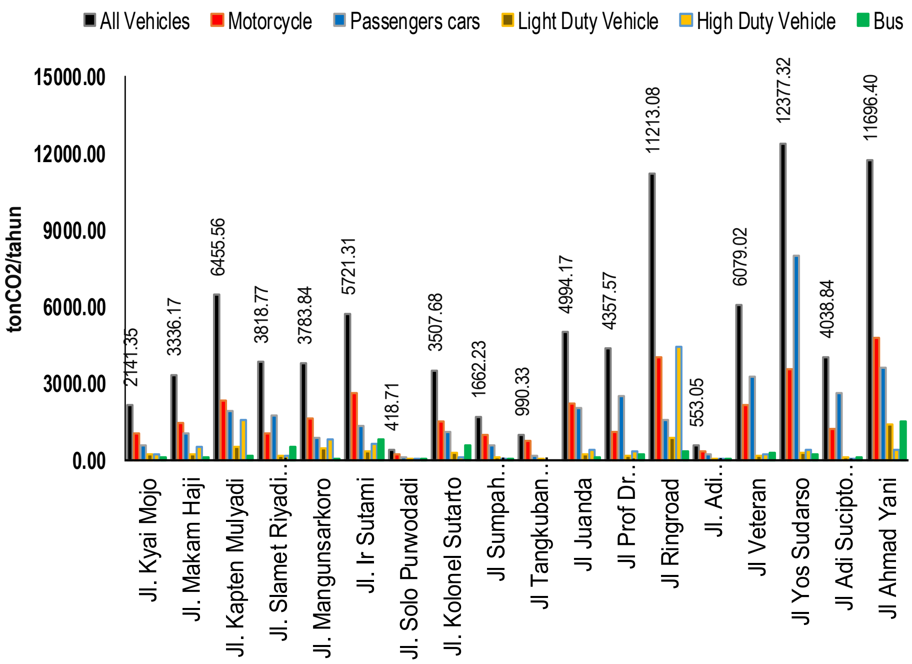

Figure 2. Emissions (tonnes CO_2e/year) released by transportation activities on each segment of gateways and transit access points in Surakarta

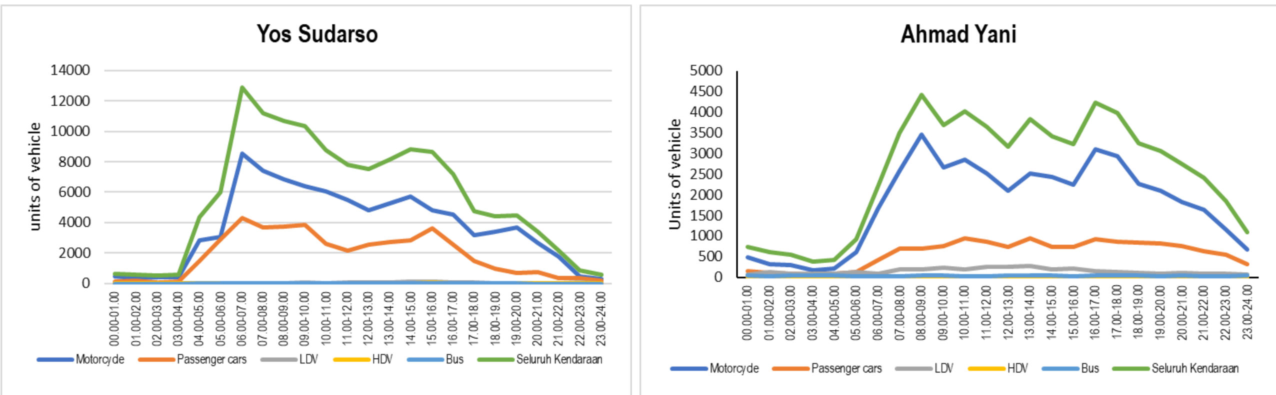

Figure 3. Daily pattern comparison between road sample of gateways (left) and transit access (right) in Surakarta

convenience through private modes. In Indonesia, public transportation users are generally much lower in number than private vehicles, especially motorcycles (Selamena et al., 2021). To further understand the emission contributors, this study also interviewed the public and users of the Batik Solo Trans (BST), a public transportation system in Surakarta, which revealed that the low interest in using public transportation can be associated with suboptimal BST services, including limited routes and feeder services in the hinterlands.

Dense residential areas of commuters are not yet fully covered by public transportation services, as well as the location of their main destinations. Distribution of commuting areas that are not balanced by equitable public transportation will increase emissions. (Zheng et al, 2011). This is inconsistent with the concept that emissions accumulate more at residential points and trade centers (Liu et al, 2022). Population, economic aggregation, and motor vehicle travel volume have a more significant relationship to transportation emissions than the energy consumption ratio (Lei et al, 2023). This study found that in Surakarta City, there is a significant positive correlation between transportation emissions and dense residential areas (r: 0.740), population size (r: 0.600), and the presence of trade and service areas (r: 0.591). The theory and reality show that BST service planning has not been optimally designed to reduce urban transportation emissions in Surakarta.

The traffic scenario on the gate and transit lines is dominated by free flow (37.15%) and heavy traffic (34.9%). This scenario shows that motorized vehicles have been dense at gate access and transit. The stop-and-go scenario (16.65%) indicates total congestion has even occurred in several sections such as Makam Haji, Captain Mulyadi Street, and Yos Sudarso Street.

The policy of improving road and pedestrian infrastructure in Surakarta tends to provide convenience to private vehicle users. Research by Nurhidayat et al (2017) found that the convenience factor determines people's preference for private vehicles. Pedestrians in Surakarta are currently utilized as parking zones, especially in the central business district. This policy contradicts research by Chee and Fernadez (2013) which recommends limiting parking spaces. Rasca and Saeed's (2022) research complements the recommendation with an increase in parking fees. These recommendations aim to reduce private vehicle ownership through reduced operational convenience.

Further analysis of secondary data from the Department of Transportation showed an increase in the number of commuters' vehicles at gateways from December 2019–2022, except for a momentary decline in 2020, when mobility restriction policies to curb the spread of the global COVID-19 pandemic were imposed. The same effect of the pandemic on traffic volume was also identified in Jakarta, Indonesia, and Wakayama, Japan (Selamena et al., 2021). Also, Sutton-Parker (2021) and Noussan and Jarre (2021) explained that the mobility restrictions shifted many activities to online meetings and transactions, thus reducing total CO_2 emissions from commuting. However, after the mobility restrictions were lifted, Surakarta saw a high "rebound" in emissions.

4. Conclusion

According to the findings of the study, the value of carbon dioxide emissions from road transportation in Surakarta City reached 722795.3 tons of CO^2 per year. Commuter and transit activities are the main factors in determining Surakarta's emissions. Emissions from major roads reached 173135.97 tons of CO_2 with 50.33% contributed by commuter and transit activities. The value of this contribution is equivalent to 133.77% of local vehicle emissions on major roads. The distribution map of road transportation emissions in Surakarta City shows a greater accumulation of gateways as commuter lines and transit access points. Transportation emissions from commuting and transit activities are mainly contributed by private modes, namely passenger cars (38.26%) and motorcycles (37.71%). This condition shows the dominance of private use and the reluctance of commuters to take advantage of public transportation. Commuter and transit activities give vulnerability to the air quality of Surakarta City due to the trend of increasing intensity. This condition makes commuters and transit users feel a high sense of urgency to mitigate it.

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