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Potential Carbon Emission Savings from Children's School Commuting in Urban Areas Based on Smart Mobility Tracking

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Abstract: The use of emissions-intensive motorized transport for school commuting, particularly in urban areas, is highly concerning. Restricting the use of motorized transport and encouraging independent school mobility provides an opening for emissions reduction. Previous research has demonstrated that independent mobility is a function of various sociodemographics. The present study aims to examine the potential for reducing carbon emissions from children's school commute through the utilization of smart mobility tracking, with travel distance and sociodemographics as determinants for primary school children in Semarang City, Indonesia. The children's mobility patterns for school commutes were recorded with portable GPS tracking devices. The data were processed using GIS to analyze routes and distances. Sociodemographic characteristics related to independent mobility were examined using logistic regression. The study estimated the actual and potential carbon emissions resulting from school commute. Travel distance, along with some of the sociodemographic traits, was analyzed to identify children's potential for independent mobility and the resulting emissions reduction. The findings indicate that increasing the chance of children's independent mobility could considerably contribute to lowering carbon emissions related to school commutes.

Keywords: carbon emission, children independent mobility, GPS, school commute, smart mobility tracking, sociodemographic characteristics

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1. Introduction

In recent decades, motorized modes for children's home-to-school trips have become more common, especially in urban areas. The decline in children's mobility is often associated with increasing levels of urbanization [1]. Furthermore, a significant number of parents are limiting their children's independent mobility due to apprehensions regarding traffic safety and the potential risks posed by other adults [2]. According to studies, children's independent mobility has significantly decreased in Finland over the previous 20 years [3]. As a growing proportion of children are driven to school by their parents, many active independent mobility activities undertaken by primary school children have been replaced by those conducted in motorized modes [3]. Other research shows that in New Zealand over the last 20 years, the use of cars for school commutes has increased by around 27% [4]. Research conducted by Putri et al. [5] and Rini et al. [6] strengthens the research trend in Finland and New Zealand, namely in Surakarta City, Indonesia, where parents prefer motorized transportation, especially motorcycles, for trips to primary school.

This trend shows an increasing need for fossil-fuel-powered motor vehicles, which significantly contribute to carbon emissions and air pollution [6, 7]. The growing carbon footprint of the transportation sector has a negative impact on air quality and exacerbates climate change [8, 9]. Children's daily mobility to and from school is non-discretionary and involves many trips [5, 10]. It is important to investigate the impact of school commutes on carbon emissions.

As smart mobility technologies and data-driven methods for tracking and controlling mobility patterns develop, research on the potential reductions in carbon emissions associated with school-age children's mobility becomes increasingly relevant and important to pursue [11]. Smart mobility solutions equipped with monitoring technology, such as GPS, present children's routes to school and provide opportunities to decrease the reliance on motorized transportation while popularizing more efficient and sustainable modes of transportation, such as cycling or walking [12, 13]. Policymakers can use data from mobility tracking systems to construct more precise green transport activities that provide insights to motivate changes in children's travel behavior, ultimately helping reduce carbon emissions in urban areas.

Travel distance and sociodemographic factors affect children's independent mobility. The distance between home and school is a significant factor that influences children's and parents' transportation choices [14–19]. It becomes harder for children to walk independently as the distance to school increases; children of primary school age can physically manage walking only up to half a mile (800 m) and can sustain trips for up to fifteen minutes [15, 20]. Children who live far from school are more likely to use motorized transportation, while those who live close to school choose to walk or cycle [21].

Furthermore, children's independent mobility is influenced by various sociodemographic characteristics, including the presence of siblings aged 18 years or under, presence of peers who take the same trip, bicycle ownership, family car or motorbike ownership, and familiarity with individuals in the surrounding neighborhood [4, 10, 18, 22–25]. An increase in independent mobility also occurs when children travel with peers, own bicycles, have siblings aged 18 or under, and familiar adults in the neighborhood [10, 25]. Thanks to an understanding of the influence of children's travel distance, mode choice, and sociodemographic characteristics, it is possible to design scenarios that take into account the potential carbon emission savings associated with children's school commutes.

Previous studies have often focused on specific aspects, such as the impact of transport on air quality [6] or the analysis of children's travel behavior separately [3, 5, 14, 26–28]. Furthermore, many studies have not fully integrated GPS-based mobility tracking technology to analyze potential carbon emission savings in the context of school-age children's travels [5, 6]. Existing studies have often focused on specific geographical areas, with many studies concentrating on specific cities and neglecting sociodemographic characteristics that may influence travel behavior [2, 3, 16, 24, 29]. This study aims to address this gap by using a smart mobility tracking approach in an urban area to assess potential carbon emission savings in children's school commutes. The emphasis is on travel distance and sociodemographic factors as significant determinants.

2. Methodology

2.1. Study Area

The study area is located in the residential center of Semarang City, Indonesia (Fig. 1).

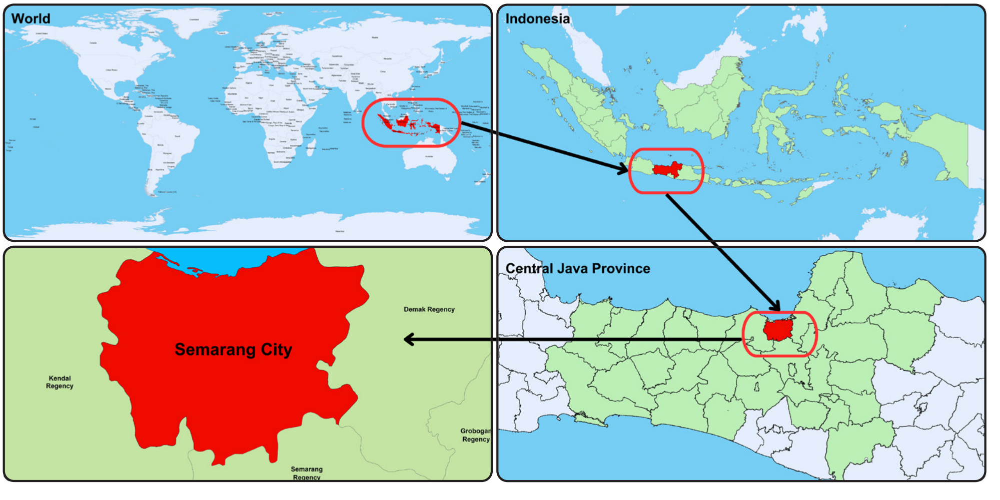

Fig. 1. Study area

As an important component of the Semarang Metropolitan area, this area is characterized by a dense residential neighborhood. Central residential zones in the city typically offer neighborhood facilities within walking distance for children, such as primary schools, thereby enhancing the potential for their independent mobility.

This study focuses on three areas: Perumnas Krapyak, Puri Anjasmoro, and Kampong Karangayu. These locations represent the characteristics of Semarang City's center residential neighborhoods, which include a public housing complex (Perumnas), a private housing complex, and an urban village (kampong). These three places have one thing in common: they all have public primary schools within an 800 m walking radius, allowing children to get to school independently, whether on foot or by bicycle.

2.2. Study Method

The study aims to examine the potential for reducing carbon emissions during children's school commutes through the utilization of smart mobility tracking, with travel distance and sociodemographic factors as determinants. It addressed three research questions:

1) To what extent do sociodemographic characteristics influence children's independent mobility to school?
2) What is the carbon emission level of school commutes based on smart mobility tracking data?
3) What is the reduction potential of carbon emissions from school commutes considering the sociodemographics?

The hypothesis predicts that sociodemographics influence independent mobility, which will support estimating the reduction of carbon emissions from school commutes.

The study focuses on primary school-aged children residing in Semarang City, Indonesia. This age group demonstrates the cognitive and physiological capacities required for mobility within defined spatial and temporal parameters; however, their spatial range remains restricted by reliance on parental permission [3, 10, 14, 19, 20, 22, 26, 30, 31].

Data collection for this study took place between April to May 2024. The sample size was calculated using the estimated interval method for an unknown population size, assuming a standard deviation of 0.25, a confidence level of 95%, and an allowable estimation error of less than 0.05 [32], yielding a minimum sample size of 96.04. Considering that each age group (7–8 years, 9–10 years, and 11–12 years) and gender (boy and girl) possess distinct cognitive characteristics and mobility thresholds, the sample size was evenly distributed across each age group and gender, with 17 children in each group, yielding a total sample size of 102 children at each study location, or 306 children across all three locations. All participants met the criteria of having resided in the area for at least 1 year and having attended a public primary school, thereby exhibiting a tendency toward stable travel patterns and homogeneous socioeconomic characteristics. Limiting the study sample to a specific socioeconomic context may yield findings that can only be generalized to other populations sharing the same socioeconomic attributes.

The objectives of this study were achieved through four stages:

1) children's school commute characteristics utilizing smart mobility tracking;
2) sociodemographic factors influencing children's independent mobility;
3) actual carbon emissions from children's school commutes;
4) potential reductions in carbon emissions from children's school commutes.

2.3. Children's School Commuting Characteristics Based on Smart Mobility Tracking

Data on children's school routes were collected using the SinoTrack GPS Portable Tracker ST-903, configured with a GSM telecommunications provider card to ensure the accuracy of the schoolchildren's route points to within 5 m. This device is small and lightweight and can be worn as a necklace or affixed to a school bag, ensuring it does not impede schoolchildren's movement or daily activities. Its 3.7 V 1,050 mAh battery powering the device will last a week, which is ideal for capturing school commutes made by children to help identify patterns and consistencies in travel within a weekday period. The Ruhavik application tracks and logs the movements of all study participants simultaneously. Accountability is ensured through the application's 5–10-second interval updates and playback recordings of the child's movement and historical route tracking.

A geospatial approach was applied to analyze these travel routes and distances. GPS tracking devices are common in similar studies because they provide accurate and reliable data on children's travel routes [33]. This methodology is an improvement over previous approaches that relied on data generated from shortest-route modeling using Geographic Information System (GIS) applications [33–34].

All parents gave consent to the collection of data on children's school routes with GPS trackers. The researchers made sure no personal data about the children, such as names and addresses, were collected. The children's starting point for the travel was determined by finding where the GPS tracker logs showed the tracked movements stopped between 6 p.m. and 6 a.m. To protect the children's home location data, this article avoids providing precise coordinates for the home and, to protect confidentiality, removes all building parcels from the map except the marked origin and destination points, thereby omitting the home's location information.

To assess the differences in travel distance and travel mode data for school journeys, two nonparametric statistical analyses were conducted. This was necessary because of the non-normal distribution of the data sets. A Mann–Whitney U test was conducted to determine differences in the distance of school commutes between children [35] with independent mobility (CIM) and those without (No CIM).

A Kruskal–Wallis H test was also conducted to determine differences among the four groups [36] in school travel distance for the different modes of transport used. The distance hypothesis assumes that within a specific nonmotorized transport distance, a travel distance falling within the CIM range reflects the presence of independent school mobility for children.

2.4. Sociodemographic Characteristics Influencing Children's Independent Mobility

Data on children's sociodemographic characteristics were obtained through a questionnaire administered after the completion of data collection via GPS tracking devices. Sociodemographic data included variables such as the presence of siblings aged 18 years or under, presence of peers who take the same trip, bicycle ownership, family car or motorcycle ownership, and familiarity with individuals in the neighborhood [4, 10, 18, 22]. For analytical purposes, data on whether a family had a car or motorcycle were not considered, as all samples uniformly exhibited this variable. This lack of variation may be a limitation, as the study's findings may only apply to populations with the same socioeconomic homogeneity as the research sample.

To understand the sociodemographic factors that determine children's independent school mobility, the logistic regression method was selected [21]. This method was appropriate because the relevant data are nominal; therefore, no normal distribution assumption is needed. The sociodemographic factors identified as significantly determining children's independent mobility will serve as key factors for modeling school travel behavior and patterns aimed at targeted reductions in carbon dioxide emissions.

2.5. Actual Carbon Emissions from Children's School Commuting

Quantitative analyses were conducted to assess both the actual and potential carbon emissions from children's school commutes, to identify potential carbon emission savings. Pursuant to the Regulation of the Minister of Environment of the Republic of Indonesia Number 12 of 2010 regarding the Implementation of Regional Air Pollution Control, carbon dioxide (CO_2) emissions from motor vehicle exhaust are calculated using Equation (1) [37]. These guidelines are fundamentally consistent with Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories with adjustments to emission factors to account for the transportation modes and vehicle fuels used in Indonesia (see Table 1) [37, 38].

$$E_a = \sum_{b=1,c=1} (VKT_{b,c} \cdot FE_{a,b,c}) \tag{1}$$

where: E_a – total emissions of gas pollutant a [g], $VKT_{b,c}$ – travel distance for vehicle type "b" and fuel type "c" [km], $FE_{a,b,c}$ – emission factor for gas pollutant, vehicle type "b", and fuel type "c" [g/km].

Table 1. Vehicle emission factor

Vehicle Type	CO_2 [g/km]
Motorcycle (petrol fuel)	3,180
Car (petrol fuel)	3,180

Source: [37]

2.6. Potential Reductions in Carbon Emissions from Children's School Commuting

For the final stage of the study, the possible carbon emission reductions associated with children's school commutes were analyzed from a subset of research that met the following criteria:

- Children whose school transportation did not include independent mobility, as parents picked children up and dropped them off using motorized vehicles.
- Study participants fulfilling all sociodemographic criteria influencing children's mobility as laid out in the second stage of the study.
- Children whose school commute distance was 800 m or less, which is the distance considered feasible for walking. This specific research is limited, as it does not explore the factors influencing children's route selection preferences. Thus, for the carbon-emission reduction analysis, the distance criterion was the actual distance of the school commute rather than the shortest possible route.

Children who satisfy these three criteria may be able to move independently to and from school by walking, cycling, or taking other forms of non-motorized transportation. If children can engage in independent mobility to school, then the carbon emissions impact will be zero [37]. Estimating a reduction in carbon emissions to zero for children who meet these criteria will illustrate the potential decrease in carbon emissions associated with children's school commutes due to the adoption of independent mobility.

3. Result and Discussion

3.1. Children's School Commuting Characteristics Based on Smart Mobility Tracking

The adoption of GPS tracking devices has become prevalent in related studies due to their reliability in providing accurate data on children's travel routes, as opposed to relying on data derived from shortest route modeling using Geographic Information System (GIS) applications [33]. Consequently, this study employs GPS tracking devices to collect data on the actual home-to-school travel routes. The travel distance and the mode of transport selected by each child are subsequently analyzed to evaluate the carbon emissions generated during their school commutes.

Figure 2a shows a distance comparison of school commutes taken by children with versus those without independent mobility (CIM). There is a substantial difference in the distance range for school commutes with independent mobility, with the minimum recorded distance being 3.52 m and the maximum 436.00 m. These trips are well within a child's walking distance. This supports the findings of Mammen et al. [15], which indicate that children with independent mobility are more likely to travel shorter distances.

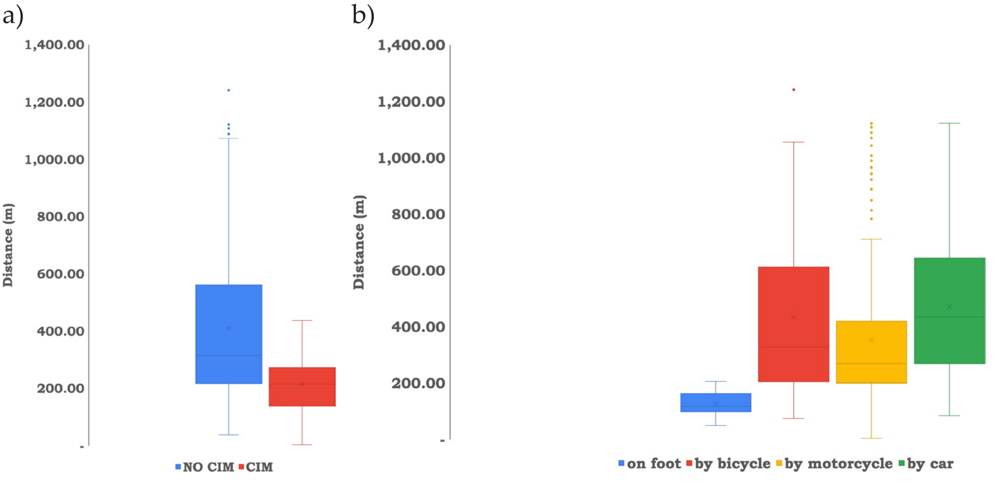

Fig. 2. Comparison of home-to-school distance based on children's school mobility behavior (a) and the type of transport mode used (b)

In contrast, children's trips where parents use motorized vehicles (No CIM) show a wider range of travel distances, from 37.89 m to 1,072.98 m. This could mean two things: (1) some children are not practicing independent mobility even though their travel distances are in the walking range [5, 6] and/or (2) some children with school travel distances over 800 m live near a primary school that is within walking distance. This could mean that some children take routes to school that are longer than the shortest path. This study highlights the limitations of the factors considered for the routes taken, which warrant further study.

Also, the findings show that 75% of children do not independently access school even when their travel distance did not exceed 561.66 m (the upper quartile limit for the No CIM category). This points to the global phenomenon of parental control over children's independent mobility, which is also evident in this study [1, 3–6].

The results of the Mann–Whitney U analyses concerning the distances of children's school commutes were presented in Tables 2 and 3. The analyses compare school commutes made by children with independent mobility (CIM) against those without (No CIM). The results in Table 2 show that only 27% of children's school commutes were undertaken independently (CIM). The findings offer smoothed-data evidence of global trends toward the decline in children's independent mobility [1, 3–6]. Moreover, the mean ranked distance suggests that school commutes made independently (CIM) were significantly shorter than those with no CIM. This means that the average distance to school for children whose parents transported them by car was greater than the average distance of independently undertaken school commutes. This is also in line with the findings by Mammen et al. [15].

Table 2. Ranks' results of Mann–Whitney U analyses based on distance of school mobility behavior

School Commute Behavior	Sample Size	Mean Rank	Sum of Ranks
No CIM	254	165.82	42,118.00
CIM	52	93.33	48,53.00
Total	306	–	–

Table 3. Results of the Mann–Whitney U test for the distance of school commute behavior

Statistic Test	Value
Mann–Whitney U	3,475.000
Z-score	−5.383
Asymptotic significance (2-tailed) value or *p*-value	<0.001

Table 3 supports the acceptance of the Ha hypothesis. The Ha hypothesis suggests that there is a difference in the distance of school commutes taken by children who are independently mobile (CIM) versus those who are not (No CIM). This is explained by the asymptotic significance (*p*-value) of 0.05 or under, suggesting the difference in distance for school commutes by both groups is statistically significant.

Given the distance of school commutes, children travel by different modes. Figure 2b presents children who use different school commute transport modes that were compared (on foot, by bicycle, by motorcycle, by car). In fact, for each transport mode, a significant proportion, 75%, of children have their school commute distance within a range that is considered acceptable for primary school children to walk.

Motorcycle school commutes cover the shortest distance. However, the distance of school commutes on foot exhibits the smallest quartile range (Q3–Q1), indicating the lowest dispersion around the median, at just 97.21 m to 161.86 m. The small box in this case suggests that the variation in data on school commute distances on foot is limited relative to the other modes of transport, indicating that the distances were fairly consistent. In contrast, the distance of school commutes by car shows the largest quartile range, as indicated by the longest box, stretching from 216.05 m to 612.51 m. Thus, the data concerning the distances for school commutes by car show the greatest dispersion, suggesting that car school commutes cover a wider range of distances, reflected in a substantial gap between the shortest and longest distances for car passengers during school commutes.

Table 4. Ranks result from the Kruskal–Wallis H test of distance school commute based on mode choice

Mode Choice	Sample Size	Mean Rank
On foot	10	30.65
By bicycle	42	108.25
By motorcycle	197	162.19
By car	57	178.37
Total	306	–

Across all considered modes of transport a clear distinction emerges, in both average trip and maximum travel distances, between children who walk or cycle to school (CIM) and those who travel by motorcycle or car (No CIM). The findings from the study area are consistent with Ayllón et al.'s research, which reports that children who live farther from school are more likely to use motorized transport than those living closer [21].

As shown in Table 4, most respondents, 64.38%, reported using motorcycles as their mode of transport, whereas walking accounted for the smallest share, at 3.27%. This finding is consistent with the results of Putri et al.'s [5] and Rini et al.'s [6] studies, which noted a trend toward parents preferring motorized transport, especially motorcycles, when taking their children to school.

The distance traveled shows that the average travel distance ranking for walking and cycling is significantly lower than that for motorized transport modes. Considering the mean ranks, it appears that children using non-motorized modes (walking and cycling) average a shorter distance to school than children using motorized modes (motorcycles and cars). This is consistent with the literature, which suggests a tendency for motorized transport to be used, especially among children living farther from school [21].

Table 5 shows the results of the Kruskal–Wallis H test, which analyzes differences in the distance of school commutes for children who walked, cycled, or were driven by car or motorcycle to school. The asymptotic significance value is 0.001, which is less than the 0.05 level of significance; thus, the alternative hypothesis is accepted. That is, there are differences in travel distances among the various modes of transport, which confirms that children travel different distances to school depending on the transport mode used. Example of actual school commute routes taken by children for each mode of transport are shown in Figure 3.

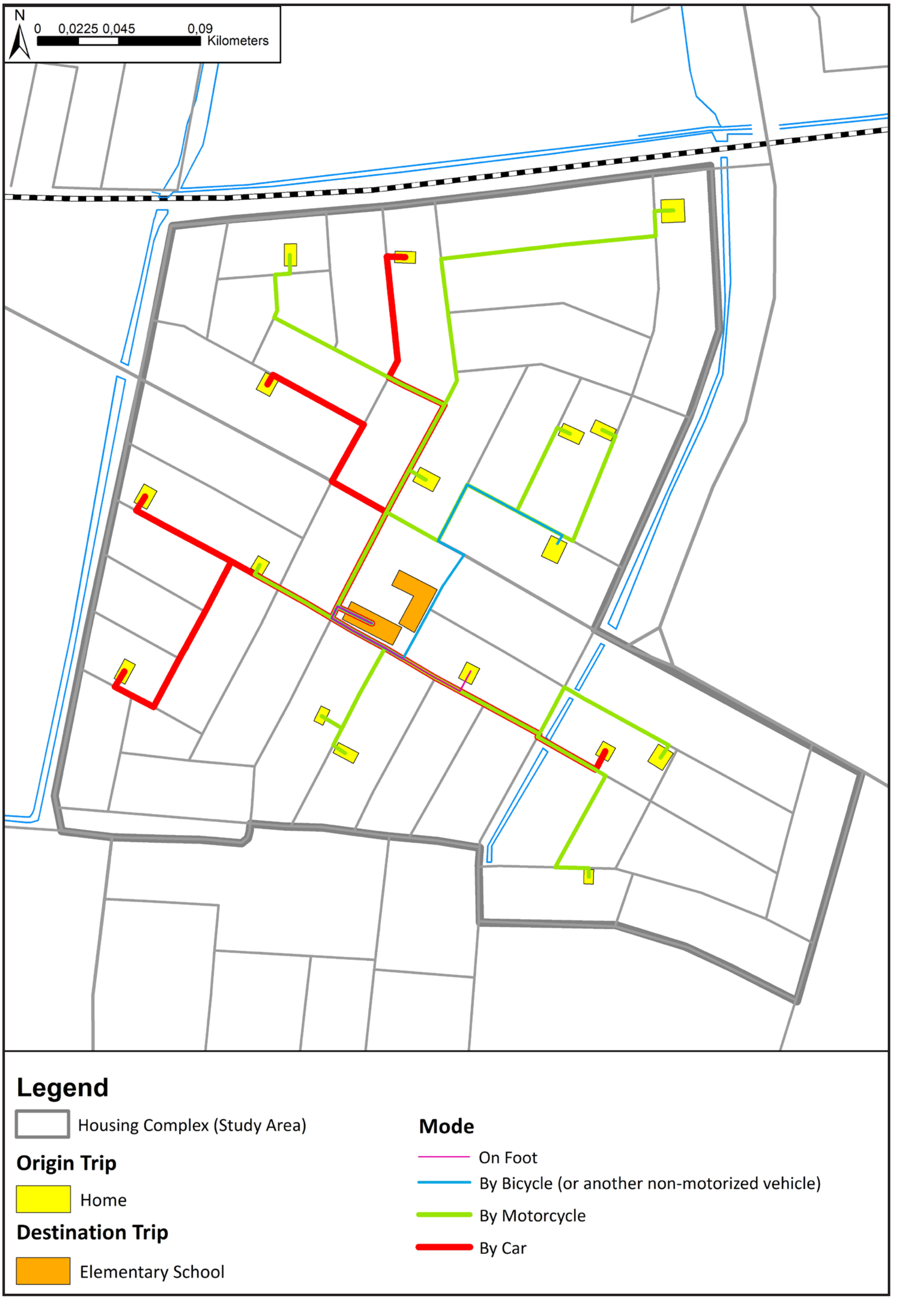

Fig. 3. Example of actual school commute route by mode

Table 5. Results of the Kruskal–Wallis H test of distance school commute based on mode choice

Statistic Test	Value
Kruskal–Wallis H	36.666
Degrees of freedom (df)	3
Asymptotic significance value (*p*-value)	<0.001

The distance from home to school is frequently a critical factor influencing both children's and parents' transport mode choices [21]. Children residing farther from school are more inclined to rely on motorized vehicles, whereas those living in closer proximity tend to walk or cycle. This trend is corroborated by studies which indicate that motorized transport, particularly motorcycles, is the preferred option among parents for facilitating access to primary schools [5, 6].

3.2. Sociodemographic Characteristics Influencing Children Independent School Mobility

Sociodemographic characteristics influencing children's independent mobility include having siblings aged 18 years or under, traveling with peers, bicycle ownership, family car or motorcycle ownership, and familiarity with individuals in the neighborhood [10, 25]. This subsection examines a logistic regression analysis aimed at understanding the sociodemographic factors that significantly affect children's independent mobility. For analytical purposes, data on whether a family owned a car or motorcycle were excluded, as all samples showed this variable consistently.

As reported in Table 6 and based on the significance value below 0.001, the overall model's fitted significance value is below 0.05, indicating that the model is statistically significant overall. Statistically, the null hypothesis (H0) is rejected, indicating that the independent variables included have a meaningful influence on the model, and the model is adequate.

Table 6. Result of the Omnibus test of model significance

Processes	Chi-square	Degree of Freedom (df)	Significance (*p*-value)
Step	74.342	4	<0.001
Block	74.342	4	<0.001
Model	74.342	4	<0.001

The model explains the Nagelkerke R square value of 0.361 and the Cox & Snell R square value of 0.216 (see Table 7). Based on these table, the independent variables explain 36.1% of the dependent variable, indicating that 63.9% of the dependent variable is not explained and may be due to variables not included in the model.

Table 7. Result of the Pseudo R-squared test of model explanatory

Cox & Snell R square	Nagelkerke R square
0.216	0.361

In Table 8, the overall model shows a fitted significance level of 0.002, which is below 0.05, and therefore supports the rejection of H0 (null hypothesis). This implies that the model is not satisfactory and, due to the significant difference between the model and the observed values, hypothesis testing is not viable. This prompted further analysis involving the interaction variables presented in the results of Table 9.

Table 8. Result of the Hosmer–Lemeshow test of model fit significance

Step	Chi-square	Degree of Freedom (df)	Significance (p-value)
1	16.581	4	0.002

As shown in Table 9, the interaction among multiple independent variables yields p-values below 0.05, indicating that each interaction variable significantly predicts children's independent mobility (CIM). Although each variable independently may not exhibit significant impact, the combination of two variables substantially impacts CIM. This finding suggests that to enhance the likelihood of children's independent mobility, all four sociodemographic factors must be satisfied, such as having siblings aged 18 years or under, having friends accompany children on journeys, having bicycles, and having familiar adults in the neighborhood. Therefore, this is still consistent with previous studies that suggest that sociodemographic factors positively affect children's independent mobility [10].

Table 9. Result of the Wald test of interaction variables of sociodemographic factors

Interaction Variables	Beta Coefficient	Standard Error	Wald	Significance (p-value)
Presence of peers sharing the same trip, and Ownership of bicycle	7.511	2.523	8.862	0.003
Presence of siblings aged 18 or under, and Presence of peers sharing the same trip	−3.915	1.327	8.702	0.003
Presence of siblings aged 18 or under, and Familiar adults in the neighborhood	3.848	1.245	9.553	0.002
Familiar adults in the neighborhood, and Presence of peers sharing the same trip	−3.558	1.404	6.421	0.011
Constant	−16.133	4.411	13.374	0.001

In Table 10, the children who fulfill all four sociodemographic variables account for 28.78%. Within this group, only those who use a motorcycle or car for parental transport to school and do not take the travel independently (No CIM) are included. Logistic regression analysis revealed that sociodemographic variables affect children's independent mobility. Among the 28.78% of child respondents, opportunities exist to modify their school travel patterns toward independent mobility, specifically walking or cycling.

Table 10. Children's sociodemographic characteristics [%]

School Commute Behavior	Presence of Siblings Aged 18 Years or Under	Presence of Peers Sharing Same Trip	Ownership of Bicycle	Familiar Adults in Neighborhood	Fulfilling All Sociodemographic Characteristics
CIM	15.03	15.69	16.99	16.01	8.50
No CIM	39.22	30.07	64.05	36.27	28.78

3.3. Actual Carbon Emissions from Children's School Commuting

Actual carbon dioxide (CO_2) emissions refer to the average amount of emissions produced per child during the school commute, quantified in grams per kilometer (g/km) per week. The actual CO_2 emissions column in Table 11 highlights how the average carbon emissions produced per child during the school commute varied depending on the actual distances and the modes of transport. Walking or cycling to school was classified as producing zero CO_2 emissions. On the other hand, the CO_2 emissions from motorized transport were generated when children were driven to school by parents by car or motorcycle [37, 38].

Table 11. Comparison of average actual CO_2 emission and potential CO_2 emission

Distance	Mode	Actual CO_2 Emission [g/km]	Potential CO_2 Emission [g/km]	Potential CO_2 Emission Reduction	
				[g/km]	[%]
Less than or equal 800 m	on foot	0	0	0	0
	by bicycle	0	0	0	0
	by motorcycle	10,224.63	5,505.10	4,719.54	46
	by car	12,307.36	12,227.61	79.75	1
More than 800 m	on foot	0	0	0	0
	by bicycle	0	0	0	0
	by motorcycle	31,574.84	31,574.84	0	0
	by car	30,992.85	30,992.85	0	0

All children whose actual commute distances exceed 800 m travel by motorized modes. In this case, no children were found commuting independently, as this distance is greater than what primary school children can reasonably be expected to walk or cycle [15, 20].

The substantial distances traveled contribute to a greater reliance on motorized modes, which emit, on average, three times as much CO_2 during transit as children whose distance is equal to or less than 800 m. Since distance is crucial for determining emissions from motorized travel during children's school commutes, it must be prioritized in initiatives to lower their environmental impact. Fuel-powered vehicles in Indonesia, including cars and motorcycles, have relatively equivalent emissions, which complicates the problem [37].

In another classification, approximately 73.53% of children have school commutes of 800 m or less (walking distance). Yet, motorized modes, cars or motorcycles, are still used to transport them to and from school. Even though the percentage of motorcycle users is higher, the distance covered by cars is greater, leading to higher car trip CO_2 emissions compared to trips by motorcycles. Children classified as having an actual school commute length of 800 m or less and using motorized modes are considered to have the potential for independent mobility, which could be walking or cycling. Adopting independent mobility for school commutes would eliminate their carbon dioxide emissions per week to zero.

The analysis of carbon emissions from children's school commute indicates that the distance and mode of transport are two primary factors that public policy officials need to consider when intervening to foster children's independent mobility to school. Such an intervention may then extend to daily, non-discretionary trips, further reducing motor vehicle emissions. A reduction in reliance on fossil fuel-powered transport could significantly decrease carbon emissions and air pollution [6, 7], thereby improving air quality and mitigating the effects of climate change associated with the transportation sector's carbon footprint [8, 9].

Further investigation is warranted for two findings: (1) some school travel routes exceed 800 m, but when considering the actual distance between home and school, the distance is within a walkable range, and (2) for children's school commute that falls within a walkable distance, there is a higher inclination toward motorized rather than non-motorized modes. This study does not examine the reasons behind the school travel mode and route choices and thus cannot provide a complete explanation for these findings. Consequently, additional studies identifying the determinants of children's school travel route and mode choices are crucial, not only for promoting independent mobility but also for amplifying the impact of such initiatives on school commute emissions reduction.

3.4. Potential Carbon Emission Savings from Children's School Commuting

Potential carbon emission savings are understood as opportunities to reduce carbon emissions from children's commuting arising when travel behavior shifts away from motorized transport to active independent mobility, including walking and cycling. Three criteria relate to school commutes that offer opportunities for the implementation of carbon emission reductions. These include children who do not currently engage in independent mobility, children who meet four sociodemographic criteria that influence children's independent mobility, and children with an actual school travel distance or a covered walking distance of 800 m or less. For children who meet the criteria, a zero-emission scenario would demonstrate the most significant reduction in carbon emissions from school commutes associated with a positive change in independent mobility behavior.

In reference to the findings derived from the previous stage of analysis, it was established that 83.01% of children do not participate in independent mobility, 37.25% fulfill the four sociodemographic criteria that allow children to have independent mobility, and 90.52% have an actual school travel distance of 800 m or less. Nevertheless, only 24.51% of children met all the three criteria, which were subsequently used in this subsection's analysis of possible carbon emission savings from school travel.

Table 11 identifies opportunities to reduce carbon dioxide emissions from school travel. The analysis produced a 46% emission-saving estimate for children who commute by motorcycle and a 1% saving for children dropped off or picked up by car. This finding indicates the overall school-run carbon emissions that could be reduced in this scenario. Decreases in school commutes that rely on fossil fuel transport are predicted to reduce carbon emissions and air pollutants, therefore enhancing air quality and contributing to climate change mitigation.

A reduction in reliance on fossil fuel-powered transport could significantly decrease carbon emissions and air pollution [6, 7], thereby improving air quality and mitigating the effects of climate change associated with the transportation sector's carbon footprint [8, 9].

Starting with an examination of the impacts of children's travel distances, mode choice, and sociodemographic characteristics, it is possible to develop scenarios that estimate potential carbon emission reductions [12] from school travel. This study addresses a gap in the previous research by describing ways to reduce carbon dioxide emissions from urban primary school children's journeys. It emphasizes the importance of travel distance parameters and sociodemographic characteristics that encourage independent mobility. Furthermore, this study uses GPS technology to track travel routes and reduce bias in distance data, which is crucial for accurate emissions calculations. Although mode choice characteristics were included as data inputs in the emissions analysis, this study did not examine the factors that influence mode choice in children's commutes that could lower emissions. The same applies to children's preferred travel routes, as this study did not examine the factors influencing their route preferences. As a result, future studies should investigate ways to reduce carbon emissions from children's school commutes by studying the factors that impact mode choice and route preferences.

The significance of these three characteristics in increasing children's independent mobility and opportunities for reducing vehicle emissions can be considered by policymakers in formulating policies that encourage children's independent mobility. An example linked to the increase of children's bicycles is the 'Cycle to School Policy' in Brighton Hill, England, which successfully promotes the use of bicycles for independent mobility to school by mandating secure school bicycle parking and safety measures for children during school cycle commutes [39]. To maximize the selection of the shortest walking routes, the Safest Route to School Walking Plan in Phoenix, USA, collaborates with schools, parents, and the city to identify and enhance the safest and most efficient routes [40]. Enhancing children's safety during independent mobility is illustrated by the 'KidsWalk to School' program in Palm Bay, Florida, where adult supervision is organized for groups of children walking to school [41]. Also, Australian government policy includes the regulation and use of digital technologies that record, track, and communicate with children while supervising adults are present [42]. In addition, policies that promote greater independent mobility for children need to be tailored to the city's profile and the culture of the surrounding community.

4. Conclusion

This study emphasizes the use of smart mobility monitoring to minimize spatial data bias and to better understand children's actual journeys to school and the associated carbon footprints. The research shows significant differences attributable to distance, transport modality, and some interaction of sociodemographic factors that independently impact children's mobility. The fulfillment of these three criteria serves as the basis for identifying school commutes likely to lead to a shift in travel behavior, specifically from motorized transport to carbon-free, independent mobility. The findings of the study could be different if conducted elsewhere, due to differences in built environments and socioeconomic contexts of children. Nonetheless, the operationalization of the study allows for such variation to be used in other research locations.

The research findings indicate that there is a likely reduction of 46% in gas emissions for actual school commutes made on motorcycles and a 1% reduction for journeys made by cars. To implement this study's research model, it is crucial that policymakers devise plans which prioritize the three criteria to encourage independent mobility among schoolchildren, thereby achieving the goal of reducing gas emissions on school commutes. Additionally, the determinants of travel mode and route selection require attention in future studies.

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CRediT Author Contribution

R. A. P.: conceptualization, methodology, data collection, analysis, software, manuscript writing.

I. B.: conceptualization, methodology, research supervision.

A. W. S.: conceptualization, methodology, research supervision.

A. F. A.: data collection, visualization.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Requests for access to the datasets generated or analyzed during this research will be considered upon inquiry to the corresponding author.

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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