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Traffic CO_2 Emissions and Roadside-Tree Carbon Sequestration along Pemuda Road in Surabaya, Indonesia

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Abstract

Urban transportation is a major contributor to carbon emissions in high-mobility downtown corridors, while roadside vegetation is often expected to offset part of these emissions. Previous studies have compared transportation emissions with vegetation-based carbon offsets, but evidence remains limited for individual downtown road corridors using comparable annualised emission and sequestration measures. This study assesses the carbon balance along a 1.5-km segment of Pemuda Road in Surabaya by estimating annualised motor-vehicle CO_2 emissions and the carbon stock and annual sequestration of existing roadside vegetation. A 16-hour manual traffic count was conducted on 5 May 2023, and a roadside-vegetation survey conducted on 11 May 2026 identified 35 trees for aboveground-biomass estimation. The quantitative analysis integrates traffic counting, Vehicle Kilometres Travelled, vehicle emission factors, allometric biomass estimation, carbon-stock estimation, and scenario-based annual sequestration. The results show that motor vehicles generate 2,773.61 tonnes of CO_2 per year, while the 35 existing roadside trees store 85.77 tonnes of CO_2 equivalent. Under the main sequestration-to-storage scenario of 4.0%, annual vegetation sequestration is estimated at 3.43 tonnes of CO_2 per year, resulting in a net carbon deficit of 2,770.18 tonnes of CO_2 per year and a vegetation offset fraction of 0.124%. Sensitivity analysis confirms that the vegetation offset fraction remains below 0.2% across the tested scenarios. These findings demonstrate that roadside vegetation provides only a limited offset and should be positioned as a complementary mitigation strategy alongside public transport improvement, private-vehicle management, active mobility, and integrated low-carbon land-use planning.

Keywords: Transportation Emissions; Carbon Balance; Urban Vegetation; Low-Carbon Development; Surabaya,

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INTRODUCTION

Urban areas concentrate economic activity, transportation demand, energy consumption, and population, making them critical settings for climate-change mitigation. Transportation has become one of the fastest-growing contributors to greenhouse gas emissions, particularly where daily mobility remains highly dependent on private motorised vehicles and increasing travel activity (Ling et al., 2024). The expansion of built-up areas, rising vehicle ownership, and high daily mobility intensify the interaction among land use, travel behaviour, energy consumption, and transportation-related emissions (Huang et al., 2022; Yang et al., 2024).

As East Java's main economic centre, Surabaya is under significant strain from urban mobility. Surabaya is a major city that functions as a centre for public activities, government, trade, services, and education. These activities generate substantial travel demand, particularly towards the downtown area. Road corridors provide an important analytical unit because land use, transportation activity, and urban vegetation interact directly at this scale. Pemuda Road is a major downtown corridor connecting shopping centres, workplaces, accommodation facilities, public

spaces, and urban tourism destinations such as Surabaya Plaza and the Submarine Monument. These characteristics contribute to high activity levels and substantial traffic volumes along the corridor.

Recent studies explain the relationship between the built environment and transportation emissions through multiple spatial dimensions, including population and development density, land-use diversity, street-network characteristics, destination accessibility, and proximity to public transport. These characteristics influence travel distance, mode choice, traffic intensity, and the resulting transportation-related carbon emissions (Huang et al., 2022). Gao et al. (2022) further demonstrate that population density, land-use diversity, road density, and access to metro stations have nonlinear and spatially differentiated effects on trip-level CO_2 emissions. Urban form and transportation development may also interact in shaping daily travel emissions, as more accessible and polycentric spatial structures can shorten travel distances and support lower-carbon mobility patterns (Yang et al., 2024). Consequently, the integration of land-use patterns, road-network configuration, and transportation systems at the urban micro-scale is important for understanding variations in transportation emissions across road corridors (Boeing et al., 2024; Huang et al., 2022).

Urban greenery is frequently promoted as a nature-based component of climate-change mitigation. Urban trees contribute to climate mitigation by storing carbon in woody biomass and by sequestering additional atmospheric carbon as they grow, while also providing microclimate, air-quality, and public-space benefits. The magnitude of carbon storage and annual sequestration varies according to tree species, size, health condition, vegetation structure, and management practices. Recent assessments show that species composition and tree structural characteristics substantially influence urban carbon storage and annual sequestration, demonstrating the importance of quantifying these two components separately when evaluating urban vegetation as a carbon sink (Ma et al., 2021; Moreno et al., 2024; Strashok et al., 2025).

Pemuda Road provides a relevant setting for this assessment because it combines high transportation activity, intensive urban land uses, and limited roadside planting space within a central-city corridor. Evaluating the balance between transportation emissions and annual vegetation sequestration can clarify the actual mitigation contribution of existing roadside trees without treating vegetation as a substitute for source-level emission reduction.

This study aims to estimate annualised motor-vehicle CO_2 emissions, quantify the carbon stock and scenario-based annual sequestration of existing roadside vegetation, and assess the resulting carbon balance along Pemuda Road in Surabaya. Specifically, the study asks: to what extent can existing roadside trees offset annualised observed-day traffic CO_2 emissions along a high-activity downtown road corridor? The contribution of this study is primarily empirical and analytical rather than methodological. It provides corridor-specific evidence by spatially matching traffic activity with an inventory of roadside trees, distinguishing accumulated carbon storage from annual sequestration, and testing whether alternative sequestration assumptions alter the estimated carbon imbalance. The findings are subsequently used to identify implications for transport-emission reduction and complementary roadside-vegetation management in Surabaya.

METHOD

1. Study Area

The study was conducted along a 1.5-km segment of Pemuda Road in central Surabaya, East Java, Indonesia. Pemuda Road is one of the major urban corridors located in Genteng District, particularly within Embong Kaliasin Urban Village. The corridor is characterised by intensive commercial, office, public-service, and recreational activities and is located near major activity centres, including Plaza Surabaya, the World Trade Center Surabaya, and Balai Pemuda. These land-use characteristics generate substantial daily travel activity and make the corridor relevant for assessing the relationship between transportation-related CO_2 emissions and the carbon-sequestration contribution of existing roadside vegetation.

The study corridor extends approximately 1.5 km along Pemuda Road. Manual traffic observations were conducted from a pedestrian-overpass observation point located along the corridor. The traffic count covered westbound traffic and was conducted on 5 May 2023 from 05:00 to 21:00. The vegetation component covered 35 existing roadside trees identified through the primary vegetation survey along the study corridor. Figure 1 presents the location of Pemuda Road within Surabaya and the spatial extent of the study corridor and traffic-observation point.

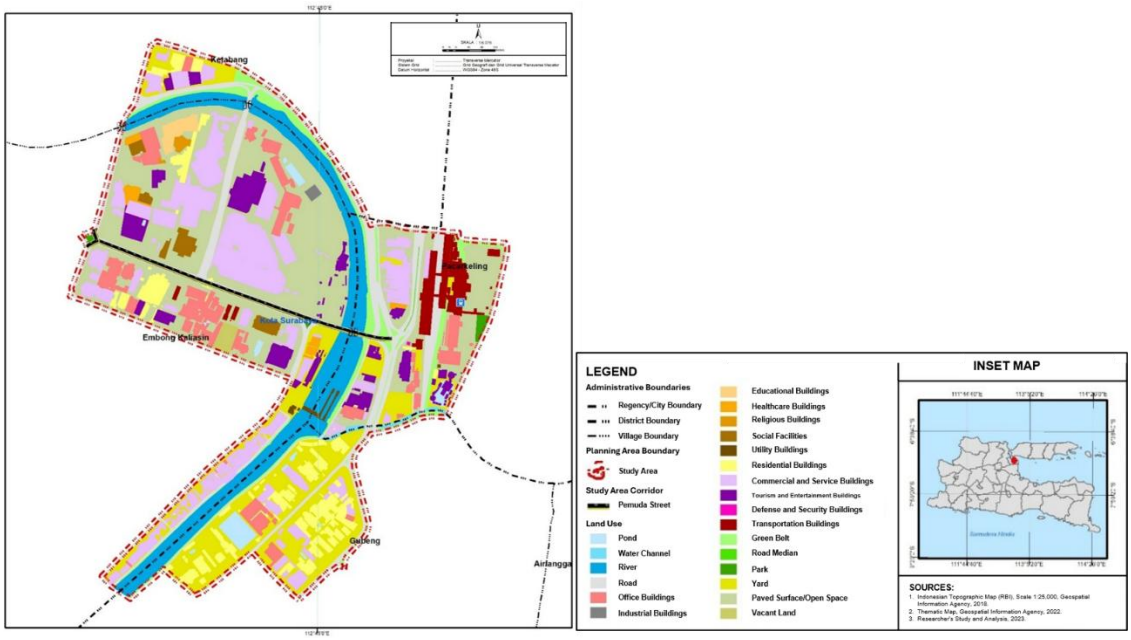


Figure 1. Location of the 1.5-km Pemuda Road Study Corridor in Surabaya, Indonesia

2. Traffic Survey and Vehicle Emission Estimation

The traffic survey was conducted manually at the pedestrian-overpass observation point on Pemuda Road on Friday, 5 May 2023, from 05:00 to 21:00, covering 16 consecutive hours. Four surveyors recorded westbound traffic at 15-minute intervals under clear-weather conditions. Vehicles were classified as motorcycles, private cars and taxis, public minivans, pick-up or box vehicles and mini-trucks, heavy vehicles, and non-motorised vehicles. The interval records were aggregated by hour and then summed across the full observation period. The values of 78,798 motorcycles, 8,655 private cars and taxis, 603 light commercial vehicles, and 171 non-motorised vehicles are cumulative direct counts for the 16-hour survey. No additional expansion factor was applied. These totals were used as the observed-day traffic proxy in the VKT calculation. Non-motorised vehicles were excluded from direct combustion-emission calculations.

The Vehicle Kilometres Travelled (VKT) method was used because fuel-consumption data were unavailable. For each vehicle class, the cumulative 16-hour count was multiplied by the 1.5-km corridor length. The resulting value represents kilometres travelled per observed day, using the survey-day count as a daily proxy. Daily emissions were annualised by multiplication by 365. This procedure assumes that the survey day observed represents a typical operating day and does not constitute annual average daily traffic (AADT).

The formula used to calculate VKT is:

$$VKT_i = N_i \times L \quad (1)$$

where VKT_i is vehicle kilometres travelled for vehicle class i in km per observed day, N_i is the cumulative 16-hour vehicle count used as the observed-day proxy, and L is the corridor length in kilometres.

Daily CO_2 emissions were calculated by multiplying VKT by the emission factor for each vehicle class and converting grams to tonnes. Annual emissions were then obtained by multiplying the observed-day emissions by 365:

$$E_{(daily,i)} = VKT_i \times EF_i \times 10^{(-6)} \quad (2)$$

$$E_a annual = \sum iE(daily,i) \times 365 \quad (3)$$

Where $E_{(daily,i)}$ is daily CO_2 emissions for vehicle class i in tonnes per observed day, VKT_i is vehicle kilometres travelled in km per observed day, EF_i is the corresponding CO_2 emission factor in g CO_2/km, and 10^{-6} converts grams to tonnes. $E_a annual$ is the annualised observed-day estimate in tonnes CO_2/year. The resulting annual value is a proxy based on the observed survey day and should not be interpreted as an AADT-based annual inventory.

Vehicle-class CO_2 emission factors of 41.8 g CO_2/km for motorcycles, 191 g CO_2/km for light passenger vehicles, 197.5 g CO_2/km for light commercial vehicles, and 742 g CO_2/km for heavy

vehicles were adopted from the Indonesian national greenhouse gas inventory guidelines for the energy sector published by the Ministry of Environment and Forestry (Kementerian Lingkungan Hidup dan Kehutanan, 2018). Distance-based emission factors were used because vehicle-specific fuel consumption, engine characteristics, and direct emission measurements were unavailable. Heavy vehicles were retained as a survey category but contributed no emissions because no heavy vehicles were observed during the traffic survey. The calculation therefore represents direct vehicle-use CO_2 emissions within the study corridor and does not include vehicle life-cycle emissions or other greenhouse gases.

2.3 Vegetation Biomass and Carbon Estimation

The vegetation survey was conducted on 11 May 2026 and identified 35 existing roadside trees, predominantly Angsana (Pterocarpus indicus). DBH was measured individually for all trees at breast height using a measuring tape. For the biomass calculation, the individual DBH measurements were summarised into two size classes. Thirty larger trees had a mean DBH of approximately 40 cm, while five smaller trees had a mean DBH of approximately 15 cm. These group mean DBH values were used as representative inputs to the allometric equation. This grouped-mean approach is acknowledged as an approximation because the nonlinear relationship between DBH and biomass may produce estimates that differ from calculations based on individual-tree DBH values. A wood-density value of 0.65 g/cm^3 was applied for Pterocarpus indicus based on the Atlas Kayu Indonesia (Martawijaya et al., 2005).

Aboveground biomass was estimated using the moist-tropical allometric equation reported by Chave et al. (2005). The equation was selected because diameter at breast height and wood density were the tree-level variables available in this study. The model provides a non-destructive approximation of aboveground biomass. Because it was developed from tropical forest trees rather than open-grown roadside trees, its application to urban street trees is treated as a methodological approximation.

$$AGB = \rho \times exp(-1.499 + 2.148ln(D) + 0.207(ln(D))^2 - 0.0281(ln(D))^3 \quad (4)$$

where AGB is aboveground biomass in kilograms, ρ is wood density in g/cm^3, and D is diameter at breast height in centimetres.

The estimated aboveground biomass was then converted into carbon stock using a carbon fraction of 0.47, following the default carbon fraction for aboveground biomass recommended by the IPCC (2006).

$$C = AGB \times 0.47 \quad (5)$$

Where C represents aboveground carbon stock and AGB represents aboveground biomass. The carbon fraction of 0.47 corresponds to the IPCC default value for converting dry aboveground biomass to carbon.

2.4 Carbon Balance and Sensitivity Analysis

Carbon stocks are then converted to carbon dioxide equivalents using a conversion factor of 3.67. This factor is derived from the ratio of the molecular mass of CO_2 to that of carbon. The formula used is:

$$CO_2 = C \times 3.67 \quad (6)$$

This value represents stored carbon expressed as CO_2 equivalent and cannot be compared directly with annual vehicle emissions. Annual vegetation carbon sequestration was therefore evaluated as a scenario-based flux because tree age, planting year, and repeated annual DBH measurements were unavailable. A 4.0% sequestration-to-storage ratio was adopted as the main literature-informed scenario, consistent with the approximate range reported in recent urban-tree assessments: Rossi et al. (2022) imply gross and net ratios of approximately 4.13% and 3.50%, respectively, while Strashok et al. (2025) imply a gross ratio of approximately 3.61%. Lower and upper scenarios of 2.7% and 5.5% were retained as illustrative sensitivity tests around the main benchmark. These values are not interpreted as statistical confidence limits. Instead, they are used to test whether plausible variation in the assumed sequestration-to-storage ratio changes the substantive carbon-balance conclusion.

The annual carbon deficit was calculated by comparing annual vehicle emissions with annual vegetation carbon sequestration:

Net carbon deficit = Annual vehicle emission – Annual vegetation carbon sequestration **(7)**

The vegetation offset fraction was calculated as the percentage of annual vehicle CO_2 emissions offset by estimated annual vegetation carbon sequestration:

$$\textit{Vegetation offset fraction} = \frac{\textit{Annual vegetation carbon sequestration}}{\textbf{Annual Vehicle Emissions}} \textit{ x 100\%} \quad \textbf{(8)}$$

To provide an intuitive indication of the scale of the vegetation-emission imbalance, an illustrative tree-equivalent estimate was calculated by dividing annualised corridor traffic emissions by the weighted-average annual sequestration per existing tree under each sequestration scenario. This linear extrapolation assumes that additional trees would reproduce the size distribution and average sequestration performance of the current 35-tree inventory. The resulting values are used only as scale-equivalents and are not interpreted as planting targets.

A complementary modal-shift-equivalent sensitivity analysis was also conducted to examine the relative effect of reducing private motorised travel. Because mode-specific passenger occupancy, receiving-mode capacity, and incremental public-transport emissions were unavailable, the analysis does not simulate transfers to a specific receiving mode. Instead, motorcycle and private car/taxi VKT were reduced illustratively by 10%, 20%, and 30%, while light-commercial-vehicle activity and the main vegetation-sequestration estimate were held constant. These scenarios represent reductions in private motorised travel that could potentially arise from modal shift, travel-demand management, or active-mobility improvements and should be interpreted as sensitivity tests rather than forecasts of policy implementation.

The results were used to determine whether the corridor has a carbon surplus or deficit. A carbon deficit occurs when annual vehicle CO_2 emissions exceed the estimated annual carbon sequestration of existing roadside vegetation.

RESULT AND DISCUSSION

1. Traffic Volume and Vehicle Composition

Traffic counts show that motorcycles dominate observed motorised traffic on Pemuda Road. Table 1 summarises the vehicle volumes used in the emissions calculations. The survey recorded 78,798 motorcycles, 8,655 private cars and taxis, 603 public minivans, pick-up or box vehicles and mini-trucks, no heavy vehicles, and 171 non-motorised vehicles. Non-motorised vehicles were excluded from direct combustion-emission calculations. The observed composition confirms that private motorised vehicles, particularly motorcycles, dominate the study corridor.

Table 1: Recapitulation of Vehicle Volume Based on Traffic Counting Results

Vehicle Type	Total Vehicles	Calculation Note
Motorcycle	78,798	Calculated as an emission source
Private Car and Taxi	8,655	Light passenger vehicle
Public Minivan, Pick Up/Box, Mini Truck	603	Light commercial vehicle
Heavy Vehicle	0	Not noted throughout the observation time
Non-Motorized Vehicle	171	Excluded from direct combustion-emission calculations

Motorcycles accounted for approximately 89.49% of the observed motorised vehicles but contributed approximately 65.02% of estimated annual traffic CO_2 emissions. Private cars and taxis represented approximately 9.83% of observed motorised vehicles but contributed 32.63% of estimated emissions. This contrast indicates that corridor-level emissions are influenced by both traffic volume and vehicle-class emission intensity.

2. Motor Vehicle CO_2 Emissions

The Vehicle Kilometres Travelled (VKT) method was used to compute emissions based on the vehicle volume data in Table 1. The VKT computations, emission factors, and daily and annual

emissions for each motor vehicle category are displayed in Table 2. With 118,197 km/day and 1,803.33 tonnes of CO_2 emissions annually, motorcycles produced the highest VKT. With annual CO_2 emissions of 905.07 tonnes, private vehicles and taxis produce a VKT of 12,982.5 km/day. Public minibuses, pickups or vans, and minitrucks make up this category, which emits 65.20 tonnes of CO_2 annually and produces a VKT of 904.5 km/day. The Pemuda Road section's annual motor vehicle emissions totalled 2,773.61 tonnes of CO_2. Figure 2 compares observed traffic-volume share and estimated CO_2-emission share by vehicle class, highlighting that motorcycles dominate corridor traffic volume, whereas private cars and taxis account for a disproportionately larger share of emissions relative to their traffic volume.

Table 2: Calculation of Vehicle CO_2 Emissions along the Pemuda Road Corridor

Vehicle Type	VKT (km per observed day)	CO_2 EF (g/km)	Emissions (tonnes CO_2/day)	Emissions (tonnes CO_2/year)
Motorcycle	118,197.0	41.8	4.941	1,803.33
Private Car and Taxi	12,982.5	191	2.480	905.07
Public Minivan, Pick Up/Box, Mini Truck	904.5	197.5	0.179	65.20
Total				**2,773.61**

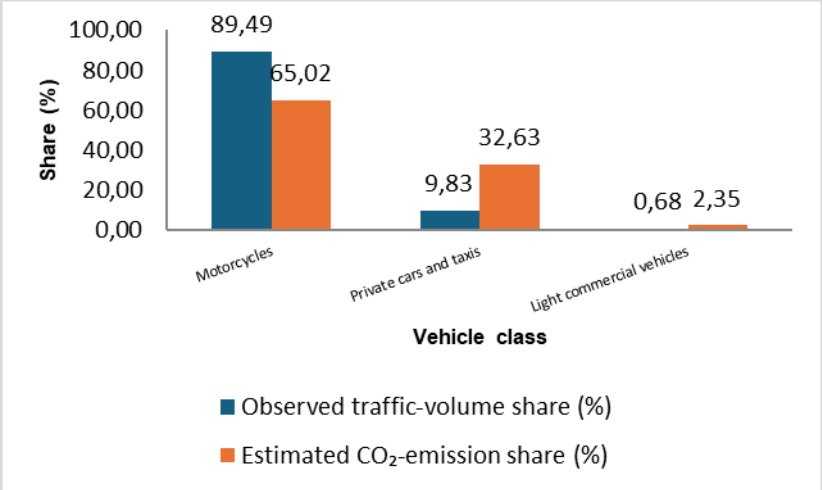


Figure 2. Observed traffic-volume share and estimated CO_2-emission share by vehicle class along Pemuda Road

3. Aboveground Biomass, Carbon Stock, and Annual Vegetation Sequestration

The vegetation inventory identified 35 roadside trees, predominantly Angsana (Pterocarpus indicus). Based on the individual DBH measurements, the 35 inventoried trees were grouped into two size categories for biomass estimation. The larger-tree group consisted of 30 trees with a mean DBH of approximately 40 cm, while the smaller-tree group consisted of five trees with a mean DBH of approximately 15 cm. Aboveground biomass was estimated using the representative mean DBH of each size class and the species-specific wood-density value with the allometric equation specified in the Methods section. Accordingly, the biomass values reported in Table 3 are grouped-mean estimates rather than sums of individual-tree AGB estimates This non-destructive approach is consistent with recent tropical urban-tree carbon assessments that combine tree structural attributes, wood density, and allometric models to estimate aboveground biomass and carbon stocks (Kurtz et al., 2024).

Table 3: Grouped-Mean Biomass Calculation of Existing Vegetation

Tree Group	Mean DBH Used in Calculation	Number of Trees	AGB per Representative Tree	Total AGB
Larger-tree group	approximately 40 cm	30 trees	1,636.31 kg	49,089.22 kg
Smaller-tree group	approximately 15 cm	5 trees	127.37 kg	636.85 kg

The value of 85.77 tonnes of CO_2 represents stored carbon expressed as CO_2 equivalent, not an annual sequestration rate. A temporally consistent comparison with annual vehicle emissions therefore requires an annual vegetation carbon-sequestration estimate. Under the main 4.0% sequestration-to-storage scenario, existing roadside vegetation is estimated to sequester 3.43 tonnes of CO_2 per year.

Table 4: Aboveground Biomass, Carbon Stock, and Stored CO_2 Equivalent of Existing Vegetation

Component	Value	Unit
Total Aboveground Biomass	49,726.07	kg
Carbon Stock	23,371.25	kg C
Stored Carbon Expressed as CO_2 Equivalent	85,772.5	kg CO_2
Stored Carbon Expressed as CO_2 Equivalent	85.77	tonnes CO_2

The value of 85.77 tonnes of CO_2 represents stored carbon expressed as CO_2 equivalent rather than carbon sequestered during a single year. Under the main literature-informed scenario, a 4.0% sequestration-to-storage ratio was applied to the stored CO_2 equivalent, resulting in an estimated annual vegetation carbon sequestration of 3.43 tonnes CO_2/year. This value is scenario-based and should not be interpreted as a direct measurement of annual biomass increment.

Table 5: Annual Vegetation Sequestration Capacity of Existing Vegetation

Component	Value	Unit
Total CO_2 Stored	85.77	tonnes CO_2
Main Sequestration-to-Storage Scenario	4.0	percent/year
Annual Vegetation Carbon Sequestration	3.43	tonnes CO_2/year

The existing roadside trees retain a measurable stock of carbon, but their estimated annual sequestration is very small relative to the annualised traffic CO_2 load of the corridor.

4. Carbon Balance of the Pemuda Road Corridor

Annualised vehicle CO_2 emissions and estimated annual vegetation carbon sequestration were compared to evaluate the corridor carbon balance. Annual vehicle emissions are 2,773.61 tonnes CO_2/year, while annual vegetation sequestration under the 4.0% main scenario is 3.43 tonnes CO_2/year. The resulting annual carbon deficit is 2,770.18 tonnes CO_2/year, corresponding to a vegetation offset fraction of 0.124%.

Table 6: Carbon Balance of the Pemuda Road Corridor

Component	Value	Unit
Annual Vehicle Emissions	2,773.61	tonnes CO_2/year
Annual Vegetation Sequestration	3.43	tonnes CO_2/year
Net Carbon Deficit	2,770.18	tonnes CO_2/year
Vegetation Offset Fraction	0.124	percent

Table 7: Sensitivity Analysis of the Annual Vegetation Sequestration Scenario

Scenario	Annual sequestration-to-storage ratio	Annual vegetation sequestration	Net carbon deficit	Vegetation offset fraction
Lower sensitivity	2.7%	2.32 tonnes CO_2/year	2,771.29 tonnes CO_2/year	0.083%
Main scenario	4.0%	3.43 tonnes CO_2/year	2,770.18 tonnes CO_2/year	0.124%
Upper sensitivity	5.5%	4.72 tonnes CO_2/year	2,768.89 tonnes CO_2/year	0.170%

The sensitivity analysis confirms that the estimated carbon deficit remains substantial across all scenarios. Annual vegetation sequestration ranges from 2.32 tonnes CO_2/year under the 2.7% lower scenario to 4.72 tonnes CO_2/year under the 5.5% upper scenario. Correspondingly, the vegetation offset fraction ranges from 0.083% to 0.170% of annual vehicle emissions. The main scenario yields 3.43 tonnes CO_2/year and an offset fraction of 0.124%. These illustrative sensitivity scenarios do not alter the central conclusion that existing roadside vegetation can offset only a very small proportion of annualised transportation emissions.

Under the main scenario, the vegetation offset fraction is only 0.124%, indicating a substantial carbon deficit along Pemuda Road. Existing roadside trees therefore provide a complementary carbon-sequestration benefit but cannot compensate for the magnitude of emissions generated by motorised traffic. Figure 3 visualises the magnitude of the annual carbon imbalance while retaining the absolute values reported in Table 7.

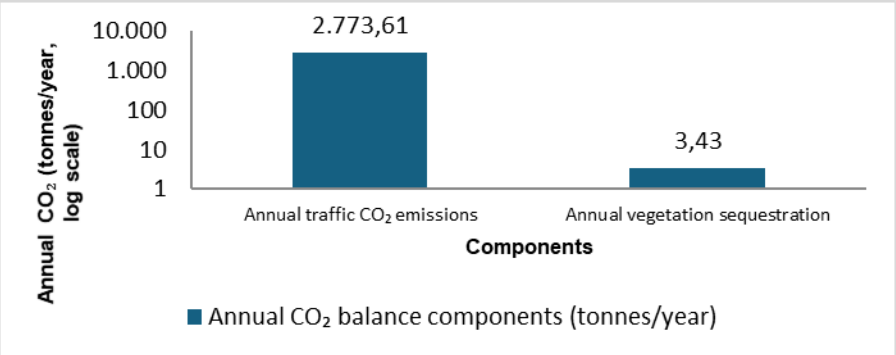


Figure 3. Annual traffic CO_2 emissions and annual vegetation sequestration along Pemuda Road (logarithmic scale)

5. Illustrative Tree-Equivalent and Modal-Shift Scenarios

Under the main 4.0% sequestration scenario, the current 35-tree inventory is estimated to sequester 3.43 tonnes CO_2/year, corresponding to a weighted-average sequestration of approximately 0.098 tonnes CO_2 per tree per year. Linear extrapolation of this average performance indicates that approximately 28,300 tree-equivalents would be required to match the annualised corridor traffic emissions of 2,773.61 tonnes CO_2/year. The corresponding scale-equivalents are approximately 41,900 trees under the 2.7% lower sequestration scenario and 20,600 trees under the 5.5% upper scenario.

Table 8: Illustrative Tree-Equivalent Estimates under the Vegetation-Sequestration Scenarios

Scenario	Annual vegetation sequestration	Approx. sequestration per existing tree	Illustrative tree-equivalent
Lower sensitivity (2.7%)	2.32 tonnes CO_2/year	0.066 tonnes CO_2/tree/year	41,900 trees
Main scenario (4.0%)	3.43 tonnes CO_2/year	0.098 tonnes CO_2/tree/year	28,300 trees
Upper sensitivity (5.5%)	4.72 tonnes CO_2/year	0.135 tonnes CO_2/tree/year	20,600 trees

Note: Tree-equivalent values were calculated using unrounded sequestration estimates and rounded to the nearest hundred. They represent illustrative scale-equivalents rather than recommended planting quantities because the calculation does not account for planting-space constraints, tree-size and species heterogeneity, survival, growth conditions, or long-term management.

The modal-shift-equivalent scenarios show a substantially larger mitigation effect from source-level travel reduction than from existing vegetation sequestration alone. Reducing motorcycle and private car/taxi VKT by 10% would lower estimated annual traffic emissions by approximately 270.84 tonnes CO_2/year, from 2,773.61 to 2,502.77 tonnes CO_2/year. Reductions of 20% and 30% would decrease annual emissions by approximately 541.68 and 812.52 tonnes CO_2/year, respectively.

Table 9: Illustrative Modal-Shift-Equivalent Sensitivity Scenarios

Scenario	Reduction in motorcycle and private car/taxi VKT	Annual traffic emissions	Emission reduction	Net carbon deficit
Baseline	0%	2,773.61 tonnes CO_2/year	0.00 tonnes CO_2/year	2,770.18 tonnes CO_2/year
Low reduction	10%	2,502.77 tonnes CO_2/year	270.84 tonnes CO_2/year	2,499.34 tonnes CO_2/year
Moderate reduction	20%	2,231.93 tonnes CO_2/year	541.68 tonnes CO_2/year	2,228.50 tonnes CO_2/year
Higher reduction	30%	1,961.09 tonnes CO_2/year	812.52 tonnes CO_2/year	1,957.66 tonnes CO_2/year

None of the illustrative VKT-reduction scenarios eliminates the corridor carbon deficit when the main vegetation-sequestration estimate is held constant. Nevertheless, even the 10% scenario reduces annual traffic CO_2 emissions by nearly 79 times the estimated 3.43 tonnes CO_2/year sequestered by the existing roadside trees. The comparison therefore illustrates the much greater mitigation leverage of source-level reductions in private motorised travel, while the tested percentages should not be interpreted as prescribed modal-shift targets.

DISCUSSION

1. Discussion: Ecological Limits of Roadside Vegetation

This corridor-scale assessment contributes new empirical evidence for Indonesian urban arterial corridors by jointly quantifying annualised traffic-related CO_2 emissions and roadside-vegetation carbon sequestration within a single, directly comparable annual offset-fraction metric. Species-level and corridor-level carbon assessments of Indonesian roadside trees remain limited (Shekina & Rachmadiarti, 2026), and few studies combine a corridor traffic census with a full carbon-balance accounting of existing vegetation rather than treating emissions and sequestration as separate assessments. The present study addresses this gap by integrating both components, together with a sensitivity analysis and illustrative modal-shift scenarios, to produce a corridor-scale carbon balance for Pemuda Road, Surabaya.

The findings reveal a substantial imbalance between annualised transportation-related CO_2 emissions and the estimated annual carbon sequestration of existing roadside vegetation. Under the main 4.0% scenario, the roadside trees are estimated to sequester 3.43 tonnes CO_2/year while storing carbon equivalent to 85.77 tonnes CO_2. Annualised vehicle emissions reach 2,773.61 tonnes

CO_2/year. The carbon deficit therefore reflects the scale of traffic emissions relative to the available annual sequestration flux rather than implying that roadside vegetation has no ecological value.

The magnitude of the vegetation offset estimated for Pemuda Road should be interpreted in relation to previous studies while recognising substantial differences in carbon-accounting approaches. Joshi et al. (2023), for example, reported 28,573.60 tCO_2e of carbon equivalent stored in avenue plantations along the Kathmandu Ring Road and 42,574.40 tCO_2e/year of vehicle emissions. These values imply an indicative stock-to-annual-emission ratio of approximately 67.1%. However, this ratio is not directly comparable with the 0.124% vegetation offset fraction estimated for Pemuda Road because the Kathmandu numerator represents accumulated carbon stock expressed as CO_2 equivalent rather than annual carbon sequestration. The present study instead compares annualised traffic emissions with scenario-based annual vegetation sequestration. Comparable corridor- and species-level assessments elsewhere reinforce this pattern of small and highly context-dependent offset fractions: a median-strip tree survey in Baghdad estimated a carbon-sequestration index of only 0.000267 relative to annualised traffic CO_2 emissions (Mohsen & Abdulkareem, 2025), while species-level sequestration estimates for Samanea saman and Pterocarpus indicus along an Indonesian arterial corridor (Shekina & Rachmadiarti, 2026) and simulated roadside-plantation sequestration in southern Quebec (Srour et al., 2024) similarly indicate that roadside-tree carbon performance depends strongly on local traffic load, tree inventory, and accounting method rather than on a fixed offset ratio.

Zulanda et al. (2024) provide a useful Indonesian comparison, although their study differs substantially in spatial scale, vegetation inventory, and estimation approach. Based on the emission and vegetation-absorption values reported for existing conditions, indicative absorption-to-emission ratios are approximately 3.26% for Subrantas Road, 6.24% for Arifin Ahmad Road, 6.18% for Sudirman Road, and 10.00% for Harapan Raya Road. These values are substantially higher than the 0.124% annual vegetation offset fraction estimated for Pemuda Road. Zulanda et al. reported considerably larger vegetation inventories, including more than one thousand existing trees on several road segments, whereas only 35 roadside trees were inventoried along Pemuda Road.

The difference should therefore not be interpreted as evidence that roadside vegetation in Surabaya is intrinsically less effective. Rather, the estimated offset depends on the quantity and structure of vegetation, species composition, available green space, traffic-emission magnitude, study extent, and carbon-accounting procedures. Zulanda et al. (2024) further demonstrated through linear-programming scenarios that substantially increasing tree numbers and the use of available urban-green-space areas could greatly increase modelled CO_2 absorption. These optimisation results represent prospective vegetation-expansion scenarios rather than existing annual roadside-tree sequestration and are therefore not directly comparable with the existing-condition offset fraction estimated for Pemuda Road.

Despite these methodological differences, the comparison with Kathmandu and Pekanbaru supports a consistent planning implication. Urban vegetation can contribute to transportation-related carbon mitigation, but the magnitude of this contribution depends strongly on the scale and characteristics of the available vegetation resource. The particularly small offset along Pemuda Road reflects the combination of a limited roadside-tree inventory and a comparatively large traffic-emission load within a spatially constrained central-city corridor. Vegetation enhancement should therefore complement rather than substitute for measures that reduce transportation emissions at source.

The contribution of urban vegetation to carbon storage and annual sequestration depends not only on the number of trees but also on tree size, species composition, stand structure, health condition, and growth performance (Ma et al., 2021; Moreno et al., 2024; Strashok et al., 2025). The vegetation inventory identified only 35 trees on Pemuda Road, where buildings, roads, walkways, utilities, and commercial activities constrain opportunities for substantial expansion of roadside vegetation.

The distinction between carbon stock and annual sequestration is also central to the interpretation of the results. The 85.77 tonnes CO_2 equivalent represents carbon accumulated in tree biomass over the trees' growth period, whereas the 2,773.61 tonnes CO_2/year generated by vehicles represents an annual emission flux. Direct comparison of accumulated carbon stock with annual emissions would therefore be temporally inconsistent at the indicator level. Carbon storage represents carbon retained in existing woody biomass, whereas annual sequestration represents additional carbon removed from the atmosphere during a given year (Moreno et al., 2024; Strashok et al., 2025).

Under the main scenario, existing roadside vegetation offsets only 0.124% of annualised transportation emissions. The sensitivity analysis reinforces this interpretation because the estimated offset remains between 0.083% and 0.170% across the tested sequestration scenarios. Increasing tree numbers alone is therefore unlikely to achieve carbon balance along the corridor, and greening should be positioned as a complementary rather than primary traffic-carbon mitigation strategy.

Roadside vegetation nevertheless provides ecosystem services beyond carbon storage and sequestration, including pollutant removal, microclimate regulation, runoff reduction, and improvements in environmental quality. The magnitude of these benefits varies with species selection, tree condition, vegetation structure, and management practices (Moreno et al., 2024; Strashok et al., 2025). Moreno et al. (2024) show that publicly managed urban trees contribute to carbon storage, annual sequestration, and air-pollutant removal, while Nero et al. (2024) report that urban-tree carbon storage is associated with stand density, stem diameter, tree height, basal area, and species composition. Appropriate species selection and long-term vegetation management can therefore strengthen ecosystem-service provision even though the capacity of roadside trees to offset traffic emissions remains constrained by the magnitude of the traffic-emission load. This ecosystem-service potential should nevertheless be considered alongside evidence that roadside trees are themselves exposed to vehicular pollutants, which can measurably alter their physiological performance and, by extension, their carbon-related functioning (Singh et al., 2020), while broader park- and city-scale assessments show that carbon-sequestration rates per unit area vary considerably with land use and management intensity (Rasoolzadeh et al., 2024) and that the offsetting role of urban street trees remains uncertain at the whole-city scale (Tang et al., 2016).

2. Discussion: Transportation as the Main Mitigation Target

Low-carbon development strategies for the Pemuda Road corridor should prioritise reducing emissions at their source rather than relying primarily on increased vegetation sequestration. Motorcycles constitute the largest source of emissions because they account for the dominant share of traffic within the study corridor. Although motorcycles have a lower emission factor per kilometre than passenger cars, their high traffic volume results in substantial aggregate emissions. This finding indicates that transportation emissions are influenced not only by vehicle-specific emission factors but also by travel activity, modal composition, and the total distance travelled. Recent transportation research identifies reducing vehicle travel, shifting trips towards lower-emitting modes, and decreasing per-kilometre emissions as complementary components of transportation decarbonisation (Ling et al., 2024) System dynamics simulations of urban transportation-management policies likewise indicate that measures such as fuel pricing and expanded public-transport service can meaningfully reduce CO_2 emissions, with combined policy packages outperforming single interventions (AlKheder et al., 2024), while cross-country evidence links transportation-system development directly to CO_2 emission trajectories in rapidly urbanising settings (Pradhan et al., 2024) and corridor-level modal-shift analysis demonstrates measurable emission reductions from shifting private car trips to public transport (Viri & Makinen, 2023)

The dominance of motorcycles and other private motor vehicles indicates that transportation-emission reduction cannot rely solely on improvements in vehicle efficiency or the introduction of cleaner vehicle technologies. Effective mitigation also requires measures that reduce private motorised travel and provide viable alternatives through public transport, walking, and cycling. Built-environment characteristics, land-use patterns, and transportation systems influence transportation-related carbon emissions by shaping mode choice, travel distance, and mobility behaviour (Huang et al., 2022). Ribeiro et al. (2024) further demonstrate that shifting private vehicle users towards public transport and active mobility can contribute directly to urban road-transport CO_2 reduction targets. At the corridor scale, these measures may include strengthening public transport services, managing parking, controlling private vehicle use where appropriate, and improving pedestrian and cycling infrastructure. Cleaner vehicle technologies should complement these travel-demand and modal-shift measures rather than replace them.

The illustrative scenario analysis reinforces this source-reduction priority. Linear extrapolation of the current vegetation performance corresponds to approximately 28,300 tree-equivalents under the main sequestration scenario, a magnitude that underscores the physical limitations of relying on roadside planting alone within a 1.5-km central-city corridor. By contrast, an illustrative 10% reduction in motorcycle and private car/taxi VKT would reduce annual

emissions by approximately 270.84 tonnes CO_2/year, nearly 79 times the annual sequestration estimated for the existing roadside trees. The 20% and 30% scenarios produce progressively larger reductions of approximately 541.68 and 812.52 tonnes CO_2/year. These scenarios do not establish policy targets, but they demonstrate the relative mitigation scale of reducing private motorised travel compared with attempting to achieve carbon balance through linear expansion of roadside-tree numbers.

Integrated land-use and transport planning provides the spatial foundation for these source-reduction measures. Chindaprasirt et al. (2024) demonstrate that scenarios combining transit-oriented development, public transport investment, and cleaner vehicle technologies can reduce transportation-related CO_2 emissions and energy consumption more effectively than isolated interventions, although their effectiveness depends on policy coverage, modal shifts, and local implementation conditions. Li et al. (2025) further show that shorter commuting distances and greater public transport use in central urban areas are associated with lower commuting emissions, whereas limited public transport accessibility and longer travel distances contribute to higher emissions in peripheral areas. These findings indicate that emission-reduction strategies along urban corridors should integrate travel-demand management, public transport accessibility, context-sensitive land-use planning, active-mobility infrastructure, and progressively cleaner vehicle technologies.

Taken together, these findings make a specific contribution to the urban carbon-balance literature. Rather than reporting vegetation carbon sequestration or transportation emissions in isolation, as in most single-component assessments (e.g., Shekina & Rachmadiarti, 2026; Srour et al., 2024; Mohsen & Abdulkareem, 2025), this study places both components within one corridor-scale accounting framework and expresses their relationship as an explicit annual offset fraction, supported by a sensitivity analysis and illustrative modal-shift scenarios. For Surabaya, and for comparable medium-density Indonesian arterial corridors more broadly, this framework offers a replicable, low-data method for identifying when vegetation-based mitigation is sufficient on its own and when it must be paired with transportation-emission reduction, thereby advancing the evidence base beyond generic assumptions that greening offsets traffic emissions.

3. Implications for Low-Carbon Development Planning in Surabaya

The carbon balance approach at the corridor scale has important implications for low-carbon development planning. First, this approach provides a quantitative basis for evaluating a corridor's ecological capacity by comparing annual emission loads with annual vegetation sequestration. Such an assessment is important because urban greening is often assumed to offset emissions without adequate measurement of the actual emission load and the sequestration capacity of existing vegetation. Rossi et al. (2022) demonstrate that tree inventories and the quantification of regulating ecosystem services can support urban green-space planning by linking vegetation structure with carbon storage, annual carbon sequestration, pollutant removal, and avoided runoff. In the Surabaya context, the findings of this study indicate that vegetation assessment should inform planting and management decisions, while vegetation planning should be integrated with transportation-emission reduction policies to achieve more effective mitigation outcomes.

Second, the study's findings indicate that source-reduction measures should take precedence over strategies that rely primarily on increasing carbon sequestration in congested urban corridors. For Pemuda Road, this entails reducing reliance on private motor vehicles, strengthening integration with public transport, improving pedestrian facilities, and managing travel demand. This direction is consistent with contemporary urban and transport planning evidence. Nieuwenhuijsen (2020) and Ribeiro et al. (2024) identify integrated land-use planning, shifts from private motorised travel to public and active transport, and travel-demand management as important pathways for reducing urban transport emissions.

Third, low-carbon development planning should integrate green infrastructure, land use, and transportation rather than treating them as separate policy sectors. Recent studies show that built-environment characteristics, including land-use composition, development intensity, road-network configuration, public transport accessibility, and the spatial relationship between residences and employment, influence travel distances, mode choice, and transportation-related carbon emissions (Huang et al., 2022; Yang et al., 2024). Li et al. (2025) further demonstrate that central urban areas with shorter commuting distances and greater public transport use tend to generate lower commuting emissions, whereas peripheral areas with limited public transport access and longer travel distances exhibit higher emissions. These findings imply that low-carbon development along urban corridors should combine context-sensitive land-use planning, improved public transport

accessibility, opportunities for shorter trips, and walking and cycling infrastructure with the enhancement of roadside vegetation. Vegetation should therefore complement measures that reduce motorised travel demand rather than substitute for transportation emission-reduction policies.

4. Policy Guidelines

The findings suggest that Pemuda Road could be considered a candidate corridor for targeted low-carbon mobility interventions rather than implying an existing formal policy classification. The very small contribution of roadside-tree sequestration relative to traffic emissions indicates that source-level emission reduction should remain the primary mitigation priority. This direction is consistent with Surabaya's current long-term spatial and development-planning framework, including the Surabaya Spatial Plan 2025–2045 and the Surabaya Long-Term Development Plan 2025-2045 (Surabaya City Government, 2024, 2025).

Relevant corridor-level measures include strengthening public-transport accessibility and intermodal connections, managing parking and private-vehicle travel demand, and improving safe, shaded, and comfortable pedestrian and cycling infrastructure. These measures can reduce reliance on private motorised travel while improving access to major activity destinations along the corridor.

Roadside vegetation should be maintained and enhanced as a complementary component of the strategy. Tree management should prioritise species suitability, long-term survival, canopy performance, and compatibility with available roadside space and infrastructure. Vegetation enhancement should not be presented as a substitute for transportation-emission reduction because the estimated vegetation offset fraction remains below 0.2% across all tested scenarios. Future corridor-scale studies in Surabaya and comparable Indonesian cities would benefit from adopting simulation-based policy-testing approaches, such as system dynamics or scenario modelling of transportation-management measures (AlKheder et al., 2024; Pradhan et al., 2024), alongside repeated, multi-species vegetation surveys of the kind conducted for Indonesian arterial-road trees elsewhere (Shekina & Rachmadiarti, 2026), to track how the corridor carbon balance evolves as both traffic-management and greening measures are implemented.

CONCLUSION

This corridor-scale assessment indicates that traffic-source reduction, rather than roadside-tree planting alone, should be the primary carbon-mitigation strategy for Pemuda Road. The 16-hour traffic count conducted on 5 May 2023 produced an observed-day proxy that annualises to 2,773.61 tonnes CO_2/year. The 35 inventoried roadside trees store carbon equivalent to 85.77 tonnes CO_2, while annual sequestration is estimated at 3.43 tonnes CO_2/year under the 4.0% main scenario.

The resulting annual carbon deficit is 2,770.18 tonnes CO_2/year and the vegetation offset fraction is 0.124%. The offset fraction remains between approximately 0.083% and 0.170% across the illustrative sensitivity scenarios. These results demonstrate a pronounced scale mismatch between annualised traffic emissions and the annual carbon-sequestration contribution of existing roadside trees.

Illustrative scenario analysis further indicates that matching current traffic emissions through linear tree-equivalent extrapolation would correspond to approximately 28,300 tree-equivalents under the main sequestration scenario, whereas a 10% reduction in motorcycle and private car/taxi VKT would reduce annual traffic emissions by approximately 270.84 tonnes CO_2/year. This comparison reinforces the priority of transportation source reduction while retaining roadside vegetation as a complementary mitigation measure.

The study therefore provides corridor-specific empirical evidence rather than a new carbon-accounting method. Roadside vegetation remains valuable for carbon storage and multiple ecosystem services, but low-carbon planning for Pemuda Road requires measures that reduce motorised travel emissions at source through improved public transport, private-vehicle and parking management, active mobility, integrated land-use and transport planning, and progressively cleaner vehicle technologies. Vegetation management should complement these measures rather than substitute for them.

There are several limitations to this study. First, traffic volume data do not accurately reflect daily, weekly, seasonal, or annual traffic fluctuations because they were collected within a certain

observation period. To improve the precision of emission estimates, future research should use multi-day traffic count data or annual average daily traffic data.

Second, vehicle age, engine technology, fuel type, speed conditions, congestion levels, and stop-and-go patterns are not represented because the calculation uses average distance-based emission factors by vehicle class. The estimate covers direct vehicle-use CO_2 within the study corridor and does not constitute a transportation life-cycle assessment. Third, the vegetation estimate covers aboveground biomass only and excludes belowground biomass. The application of a tropical-forest allometric equation to open-grown roadside trees introduces additional model uncertainty. The biomass calculation also uses representative mean DBH values for two tree-size groups rather than applying the full set of individual-tree DBH measurements directly in the allometric equation. Because the relationship between DBH and biomass is nonlinear, this aggregation may introduce additional estimation uncertainty. Future assessments should retain and apply individual-tree DBH values throughout the biomass calculation. Fourth, the study is limited to a single corridor, so the findings should not be generalised to all urban corridors in Surabaya.

The annual vegetation sequestration values are scenario-based estimates rather than measurements of annual biomass increment. The study does not include tree age, planting year, crown condition, mortality, or repeated DBH measurements. The 4.0% main scenario is informed by recent urban-tree assessments, but the underlying studies involve different species compositions, climates, vegetation structures, and modelling approaches. The 2.7% and 5.5% values are therefore interpreted as illustrative sensitivity scenarios rather than statistical confidence limits. Annual traffic emissions are likewise based on an annualised single-day observation proxy rather than AADT. Future research should combine multi-day or AADT traffic data with verified vehicle-specific emission factors and repeated tree-growth measurements.

An additional limitation concerns the temporal mismatch between the two primary datasets. The traffic survey was conducted on 5 May 2023, whereas the roadside-vegetation survey was conducted on 11 May 2026. Consequently, the estimated carbon balance combines annualised traffic emissions derived from 2023 traffic conditions with vegetation characteristics observed in 2026. Changes in traffic volume, vehicle composition, tree growth, tree mortality, or roadside-vegetation management during the intervening period may therefore affect the comparability of the two components. The resulting carbon balance should consequently be interpreted as a corridor-scale comparative estimate rather than a strictly contemporaneous carbon inventory. Future studies should collect traffic and vegetation data within the same observation period to improve temporal consistency.

The tree-equivalent and modal-shift-equivalent analyses are illustrative sensitivity scenarios rather than forecasts or prescriptive planning targets. The tree-equivalent calculation assumes linear replication of the average sequestration performance of the existing inventory and does not account for differences in tree size, species composition, mortality, growth, planting space, or long-term management. The modal-shift-equivalent scenarios represent proportional reductions in motorcycle and private car/taxi VKT without modelling the specific modes receiving shifted trips, passenger occupancy, additional public-transport operations, or associated changes in emissions. More detailed mitigation scenarios would require travel-demand, mode-choice, public-transport-capacity, and fleet-specific emission data.

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