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CASE STUDY

Ecological engineering to restore canopy connectivity and mitigate road-induced habitat fragmentation in tropical rainforests

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ABSTRACT

BACKGROUND AND OBJECTIVES: Road infrastructure and canopy fragmentation pose severe threats to arboreal primates in tropical forest landscapes. Nevertheless, observational field assessments along linear transportation corridors requently omit standardized metrics for sampling effort, spatial density uncertainties, and mechanistic causality. The study objectives were to quantify baseline primate occurrence, spatial population densities, canopy gap dimensions, and traffic-induced disturbance along a critical three-kilometer transport corridor bisecting Halimun Salak Mountain National Park, Indonesia, thereby establishing an empirical framework for canopy bridge design and engineering.

METHODS: A standardized line-transect survey was executed along a fixed three-thousand-meter belt transect representing a fifteen-hectare effective sampling area over six consecutive days, accumulating forty-eight observer-hours. Anthropogenic pressures were quantified by measuring canopy gap widths in meters and vehicular traffic volume (vehicles per hour). Primate population densities were quantified using a fixed strip-transect estimator integrated with Poisson-derived ninety-five percent confidence intervals to account for statistical uncertainty arising from twenty-six independent detections.

FINDINGS: Three sympatric endemic primate species were recorded along the corridor. Current local primate densities were recorded at 0.114 individuals per hectare (ninety-five percent confidence interval: 0.068 to 0.178) for the Javan gibbon (*Hylobates moloch*), 0.024 individuals per hectare (ninety-five percent confidence interval: 0.007 to 0.061) for the Javan grizzled leaf monkey (*Presbytis comata*), and 0.018 individuals per hectare (ninety-five percent confidence interval: 0.004 to 0.053) for the long-tailed macaque (*Macaca fascicularis*). Compared with comprehensive historical baselines from 2004, these metrics demonstrate a sharp spatial gradient in population density. Rather than capturing a direct, empirically tracked longitudinal decline, the findings indicate a localized population sink corresponding to extensive canopy gaps (12–28 m) and high traffic rates exceeding 450 vehicles per hour.

CONCLUSION: This observational study provides descriptive baseline spatial metrics rather than inferential causal modeling. The quantified canopy gap dimensions and encounter hotspots provide direct structural parameters for positioning artificial canopy bridges, mitigating physical edge effects, and restoring functional canopy connectivity for threatened arboreal primates.

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INTRODUCTION

Habitat connectivity is fundamental for preserving global biodiversity and ecosystem integrity, functioning as a vital conduit for species dispersal, gene flow, and functional resource distribution (Makwati *et al*., 2026). Nevertheless, progressive infrastructural expansion and land-use conversion have intensified landscape fragmentation across tropical rainforest ecosystems, severely impairing core ecological processes and accelerating local extinction trajectories for vulnerable taxa (Fasona *et al*., 2024). Predictive spatial modeling tools—such as maximum entropy (MaxEnt) algorithms and Circuitscape software—have advanced the capacity to identify critical connectivity pathways (Fasona *et al*., 2024). However, passive habitat protection alone is increasingly insufficient to counteract physical canopy gaps and high-density anthropogenic disturbances. Consequently, ecological engineering has emerged as an indispensable paradigm, championing structural interventions to reinstate ecosystem services and rehabilitate fragmented tropical habitats (Danneck *et al*., 2023; Oehri *et al*., 2024). Linear infrastructure, particularly transportation corridors, acts as one of the most pervasive drivers of tropical forest degradation by creating structural breaks in continuous canopy cover (Zheng *et al*., 2025). Transportation infrastructure generates pronounced edge effects that modify local microclimates and establish both physical and behavioral barriers inhibiting wildlife dispersal (Istiadi *et al*., 2024). For canopy-dwelling fauna, the removal of contiguous tree crowns forces arboreal species either to risk ground crossing—substantially increasing mortality from vehicle collisions and predation—or to remain completely isolated within degraded forest patches. Over successive generations, such enforced isolation diminishes effective population sizes, constrains gene flow, and elevates susceptibility to inbreeding depression, thereby jeopardizing the long-term persistence of forest-dependent taxa. A significant example of this global conservation issue is the tropical rainforest corridor that connects the Halimun and Salak forest blocks. Assessing habitat fragmentation along linear transportation infrastructure requires a clear distinction among distinct dimensions of ecological connectivity: structural connectivity (the physical spatial arrangement of canopy cover or artificial crossing structures), functional connectivity (the behavioral propensity and physical movement of individuals across landscape matrices), demographic connectivity (dispersal rates sufficient to influence local population growth and persistence), and genetic connectivity (gene flow mediated by successful reproduction of dispersing individuals). Infrastructure mitigation standards mainly focus on structural connectivity. However, restoring long-term population viability depends on whether structural links lead to functional, demographic, and eventual genetic connectivity. The ecological integrity of the area is impaired by a 3-kilometers (km) access road dissecting a vital forest constriction, producing an acute bottleneck effect that severely restricts fauna mobility (Mujio *et al*., 2026; Istiadi *et al*., 2024). Historical satellite evaluations revealed a 5.5 percent (%) forest cover loss driven by surrounding land conversion (Situmorang and Noviana, 2025), amplifying roadkill risks for threatened flagship species, including the Javan Hawk-eagle (*Nisaetus bartelsi*) and the endangered Javan gibbon (*Hylobates moloch*) (Widyastuti *et al*., 2023). Despite continuous surveillance initiatives, elevated vehicular traffic density along this transit corridor persistently fragments vital canopy layers, rendering endemic arboreal primates highly susceptible to localized extirpation. Although various artificial canopy bridges have been implemented globally to reconnect fragmented habitats, conventional designs often fail due to a lack of integration with species-specific locomotion biomechanics. Conventional single-rope or rudimentary ladder configurations are frequently engineered solely for mechanical strength, disregarding natural primate behavioral

ecology. Such approaches overlook interspecific variations in locomotor modes and vertical stratification. This approach ignores the different ways that different primate species move and how they are arranged vertically (Mitchell *et al*., 2022; Akhtar, 2026). For example, obligate high-canopy brachiators require structural stability and height configurations fundamentally different from those required by opportunistic mid-canopy quadrupedal climbers (Narváez-Rivera and Lindshield, 2022). Existing conservation strategies in the region remain largely restricted to biological census and passive land-use policies (Situmorang and Noviana, 2025), leaving a critical gap in multi-taxa, biomechanically aligned engineering solutions. This study integrates empirical primate locomotion tracking and traffic disturbance metrics into a structural engineering framework to construct a dual-zone artificial canopy bridge model tailored for complex canopy architectures (Damschen and Brodie, 2024). Furthermore, an integrated green engineering mitigation model was designed for fragmented rainforest corridors. By harmonizing ecological requirements with structural engineering principles, this study delivers a scalable technical prototype. The proposed model reinstates functional canopy connectivity, maintains evolutionary gene flow, and mitigates localized extinction vulnerabilities across fragmented tropical biomes worldwide. Although broad-scale ecological consequences of linear infrastructure are well-documented, a critical research gap persists regarding how localized canopy discontinuities interact with species-specific locomotion mechanics to dictate vertical and spatial corridor utilization among sympatric primates, highlighting key targets for ecological engineering and restoration. Most road ecology assessments treat canopy gaps as uniform horizontal barriers, failing to account for differing biomechanical adaptations—such as ricochetal brachiation in gibbons versus anatomical leaping limits in colobines, under variable traffic flux. Furthermore, several studies bridge empirical field assessments of geometry canopy gaps with tailored, ex-ante engineering frameworks. To address this gap, this study evaluates fine-scale canopy disjunctions of 12-28 meters (m) alongside continuous 12-hour vehicular traffic dynamics (700-1,234 vehicles 12-h) and vertical stratum positioning across three sympatric primate species (*Hylobates moloch*, *Presbytis comata*, and *Macaca fascicularis*) along the Halimun Salak transport corridor. By integrating empirical spatial encounter clusters (N = 26) with locomotion-specific crossing constraints, this study establishes a preliminary dual-zone canopy bridge design framework customized for distinct vertical strata and behavioral movement profiles. The target species include *Hylobates moloch*, *Presbytis comata*, and *Macaca fascicularis*, and the goal is to design an integrated green engineering mitigation model for fragmented rainforest corridors. Field investigations were conducted during 2025 within the vital ecological corridor linking the Halimun and Salak forest blocks within Halimun Salak Mountain National Park (HSMNP), West Java, Indonesia. To evaluate these dynamics, a 3,000-m transport corridor bisecting the Gunung Halimun Salak forest landscape was selected in West Java, Indonesia. This specific location was selected as a prime conservation bottleneck, characterized by a heavily trafficked public thoroughfare intersecting protected submontane rainforest, yielding severe canopy gaps (12-28 m) that simultaneously support three sympatric, International Union for Conservation of Nature (IUCN)-threatened primate taxa possessing divergent locomotor adaptations. This corridor serves as an empirical model for fragmented tropical rainforest landscapes across Southeast Asia, where expanding linear infrastructure compromises canopy integrity along protected area boundaries. To guide this study, four primary working hypotheses were formulated:

H_1 (Gap severity): Structural canopy disjunctions exceeding species anatomical leaping thresholds (> 8-10 m) significantly depress spatial encounter frequency along the immediate transport margin.

H_2 H2 (Traffic disturbance): Diurnal traffic peaks (> 150 vehicles/h) visually and acoustically determine lower-canopy (< 15 m) activity along the road's edge.
H_3 (Vertical partitioning): Road-margin disturbance induces upward vertical stratum shifts, forcing canopy-dependent species (*Hylobates moloch*) into upper canopy layers (>15 m) to maximize distance from ground-level noise.
H_3 (Locomotion-specific bridge acceptance): Mitigating canopy disjunctions for sympatric primate communities requires biomechanically differentiated crossing substrates (flexible walkway Versus (vs) rigid frame) matched to target locomotion profiles rather than a uniform structural design.

To establish an empirical basis for canopy bridge engineering, the current study sought to quantify baseline primate occupancy, spatial densities, canopy discontinuity dimensions, and vehicular disturbance along a critical three-kilometer transportation corridor bisecting Halimun Salak Mountain National Park, Indonesia. The study has been carried out in 2025.

MATERIALS AND METHODS

The methodological framework evaluates anthropogenic barriers to primate connectivity while formulating an integrated green engineering mitigation model by synthesizing empirical field surveys, spatial traffic dynamics, and structural engineering simulations within the fragmented matrix of HSMNP.

The study area

The study was conducted within the critical ecological corridor connecting the Halimun and Salak forest blocks in West Java, Indonesia. Topographically, the study region features a rugged mountainous terrain spanning an elevation gradient from 350 to 1,050 meters above sea level (m.a.s.l.). The primary focus of this research centered along a 3-km transportation route connecting Cianten in Bogor Regency with 6°43' south (S) and 106°39' east (E) to Cipeuteuy in Sukabumi Regency (6°46'S, 106°37'E), West Java, Indonesia. Spanning approximately 9.8 km, the roadway intersects a vital ecological matrix composed of fragmented primary and secondary tropical rainforests. The spatial configuration of this corridor is heavily influenced by surrounding anthropogenic land uses, flanked by the Cianten tea plantation to the north and residential zones alongside intensive agricultural fields to the south, as illustrated in Fig. 1.

Primate survey protocol

Along the 3,000-m belt transect, primate detections and corresponding canopy strata heights were systematically documented across six consecutive sampling days, focusing specifically on peak diurnal activity periods (06:00–10:00 and 14:00–18:00). Conducted by four trained field observers, the total visual sampling effort amounted to 48 observer-hours (8 sampling hours/day × 6 days). Observed vertical stratum positions were categorized into canopy height intervals (< 5 m, 5-10 m, 10-15 m, 15-20 m, and > 20 m) at the precise moment of initial detection.

Research design and sampling method

A standardized line-transect sampling design was established along a fixed 3,000-m (3 km) belt transect running parallel to the Garehong–Cisarua access road (east–west orientation; elevation range 800–900 m.a.s.l.) within HSMNP. Primate monitoring was carried out over six consecutive sampling days, utilizing two daily repeated passes synchronized peak diurnal activity periods (06:00–10:00 and 14:00–18:00). This resulted in a total of 12 transect walks and a cumulative observer effort of 48 observer-hours. Data collection was executed by a two-person team of experienced observers maintaining a controlled velocity of approximately 1.0 kilometers per hour (km/h) to maximize both visual and acoustic detection probabilities. The effective strip width was fixed at 50 m (25 m on each side of the transect centerline), defining an effective sample area (A) of 15 hectares (ha) (3,000 m x 50 m = 150,000 m^2 = 15 ha).

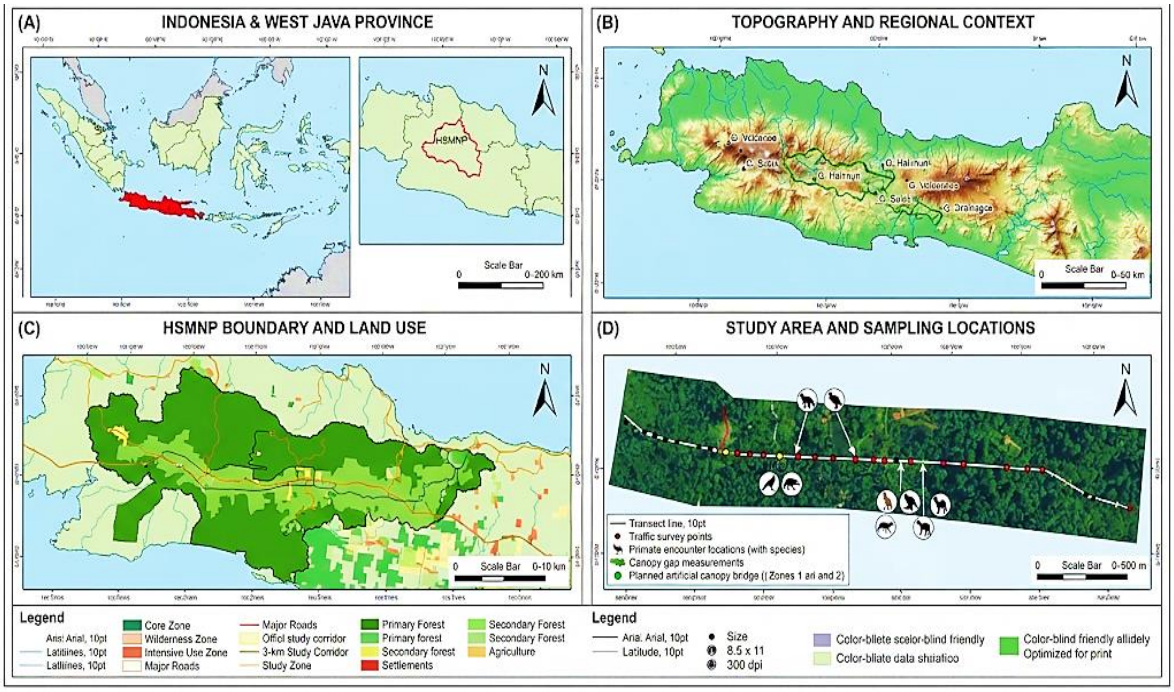

Fig. 1: Geographic location of the study area within HSMNP, West Java, Indonesia, depicting the 3-km transportation corridor connecting primary and secondary tropical rainforest blocks

Anthropogenic pressure evaluation

Physical canopy gap dimensions across the road corridor were measured using a laser rangefinder (LTI TruPulse 200). During the 6-day field survey period, vehicle traffic volume was continuously recorded over a full 12-hour period (06:00 to 18:00). Tally counters were deployed at designated roadside observation posts to systematically record hourly volumes of all transiting motorized traffic, categorized into heavy-duty trucks, buses, passenger automobiles, and motorcycles. Diurnal traffic volume varied predictably between weekdays (mean range: 700-1,000 vehicles/12h) and weekend peak periods, with the maximum single-day traffic flux reaching 1,234 vehicles/12h (recorded during peak weekend activity (Table 4).

Engineering design framework

Formulated as an *ex-ante* conceptual design blueprint, the dual-zone canopy bridge model was engineered to mitigate spatial forest disjunctions while accommodating taxa-specific locomotor dynamics. Bridge dimensions (span length: 12-28 m; attachment height: 6-8 m for Zone 1 and 15-20 m for Zone 2) were determined from physical canopy gap measurements and forest layer architecture. Detailed structural engineering analyses, including finite element modeling, static and dynamic load assessments, wind-loading evaluations, cable tensile verification, safety factors determinations, and in-situ material durability testing, exceeded the scope of this baseline ecological survey and constitute vital pre-installation engineering steps.

Population density estimation and spatial scale limitations

Population densities (D) were calculated using a fixed strip-transect formula (D = n/A), where n represents the total independent encounters and A denotes the effective sampling area of 15 hectares (3,000 m length x 50 m effective strip width). To account for statistical uncertainty associated with low sample sizes, ninety-five percent confidence intervals (95% CI) were

calculated using a Poisson distribution framework. To prevent spatial bias, density metrics were computed exclusively within the localized 15-ha corridor sampling matrix rather than extrapolated across the broader 15,000-ha national park landscape, given that roadside habitat architecture and edge disturbance gradients diverge markedly from interior forest blocks.

Parameters and data collection

Field investigations were conducted over a 3-month period from April to June 2025. This extended operational window embraced preliminary corridor mapping, physical quantification of canopy gap dimensions (m), exploratory reconnaissance, and an exhaustive vehicular traffic assessment. Concurrently, anthropogenic disturbance variables were recorded, including hourly traffic volume (vehicles/h), daily traffic intensity (vehicles/day), vehicular speed, and canopy gap widths (m). Traffic counts were recorded daily across three designated diurnal time windows (06:00–09:00, 11:00–13:00, and 15:00–18:00) to capture peak vehicular flux and diurnal activity overlaps. To establishes baseline metrics for primate distribution and vertical stratum usage, a rigorous line-transect sampling protocol was implemented over six consecutive days primary diurnal foraging windows (06:00–10:00 and 14:00–18:00), accumulating 48 observation hours across a 15-hectare effective survey area (3,000 m transect length × 50 m effective width). Population densities (D, expressed as individuals per hectare, ind/ha) for each endemic primate species—*Hylobates moloch*, *Presbytis comata*, and *Macaca fascicularis*—were estimated using a fixed strip-transect, using Eq. 1 (Buckland *et al.*, 2001; Sutherland, 2006):

$$D = \frac{n\ x\ \bar{s}}{A} \quad (1)$$

Where: n is the number of independent group encounters, $\bar{s}$ is the mean observed group size, and A is the total surveyed area (15 ha). Owing to sparse observation frequencies within this segmented landscape (N = 26 total sightings), the fitting of parametric distance-detection function fitting was precluded. To account for statistical uncertainty associated with low sample sizes, variance and 95% Confidence Intervals (95% CI) were derived using Poisson distribution confidence limits for count data. All demographic parameters and stratum utilization metrics were generated exclusively from direct field observations gathered throughout the standardized sampling period, avoiding any reliance on indirect proxies or predictive modeling for species enumeration.

Data processing and modeling workflow

The analytical workflow progressed through three integrated phases: baseline field assessment, data synthesis, and structural engineering design. To identify critical habitat bottlenecks, baseline ecological and traffic parameters were evaluated through descriptive statistical analyses and spatial density mapping techniques. Subsequently, the environmental engineering phase utilized these spatial metrics to formulate a dual-zone artificial canopy bridge model tailored to species-specific locomotion mechanics (brachiation vs. quadrupedal climbing) and site-specific canopy gaps. Ultimately, comprehensive structural validation protocols, encompassing load-bearing capacity analyses, material degradation assessments tailored to humid tropical climates, and ecological viability audits—were executed to verify that the proposed remediation design achieves both technical resilience and functional integration within tropical rainforest environments.

RESULTS AND DISCUSSION

The field assessment along the 3-km transportation corridor in HSMNP confirmed that anthropogenic road infrastructure and physical canopy disconnections present a spatial barrier for endemic arboreal primates. Elevated diurnal traffic volume (> 450 vehicles/h) and linear canopy

gaps ranging from 10 to 28 m co-occur with markedly reduced primate encounter rates along the road edge compared to historical interior baselines. These physical parameters underscore the imperative for targeted structural intervention aimed at restoring continuous canopy pathways.

Primate occurrence and population density dynamics

Systematic visual sampling across a 3,000-m belt transect, with a total effective sampling area of 15 hectares (ha), identified three sympatric endemic primate species: the *Hylobates moloch*, *Presbytis comata*, and the *Macaca fascicularis*, as summarized in Table 1. Monitoring over six consecutive sampling days targeting peak diurnal activity periods (06:00–10:00 and 14:00–18:00 monitoring yielded a cumulative total of merely 26 independent primate detections. The endangered *Hylobates moloch* recorded the highest encounters (19 sightings), corresponding to a population density of 0.114 ind/ha (95% CI}: 0.068–0.178 ind/ha). The *Presbytis comata* and *Macaca fascicularis* exhibited lower encounter rates, yielding population densities of 0.024 ind/ha (4 encounters, 95% CI: 0.007 – 0.061 ind/ha) and 0.018 ind/ha (3 encounters, 95% CI: 0.004 – 0.053 ind/ha), respectively. Developed as an empirical design framework, the dual-zone canopy bridge model formulated in this study directly accounts for localized gap geometries and the locomotor biomechanics of sympatric primates inhabiting the corridor. As physical crossing structures were neither installed nor experimentally tested within this sampling timeframe, the outlined engineering parameters function as conceptual mitigation models rather than validated conservation outcomes. Rather than claiming that the system definitively restores connectivity, the rigid frame bridge (Zone 2) is designed to minimize structural oscillation and is expected to accommodate the upper-canopy brachiation mechanics of *Hylobates moloch*. Likewis, the suspended walkway structure (Zone 1) is postulated to offer a reliable transit route tailored to the locomotor needs of quadrupedal taxa (*Presbytis comata* and *Macaca fascicularis*). Anticipated ecological benefits—such as reduced edge avoidance, restored gene flow, and long-term population persistence—remain prospective hypotheses that require empirical verification through post-construction monitoring. Benchmarking current corridor densities against regional reference data reported by LIPI-JICA (2004) indicates that local densities along the road edge (0.114 ind/ha for the *Hylobates moloch*, 0.024 ind/ha for *Presbytis comata*, and 0.018 ind/ha for *Macaca fascicularis*) are substantially lower than park-wide baseline averages (2.370, 1.250, and 0.877 ind/ha, respectively). Owing to the observational framework of this research and variations in survey methodologies, this numerical variance cannot be construed as evidence of a traffic-induced demographic decline or population trend. Instead, this spatial contrast describes a localized pattern where arboreal primate presence is severely reduced along the fragmented road edge relative to continuous forest interiors. Beyond immediate spatial displacement, this localized habitat contraction carries significant long-term implications for the persistence and demographic viability of these sympatric primates. While genetic metrics and allele frequencies were not directly measured in this empirical study, the observed physical isolation and severe spatial restriction, combined with established literature on fragmented arboreal primates (Pandey *et al*., 2025; Nijman *et al*., 2019), strongly suggest an elevated potential risk of inbreeding depression and genetic drift across the road barrier. Although the recorded spatial contraction aligns with pronounced linear canopy gaps (ranging from 12 to 28 m) and elevated vehicular traffic intensity (> 450 vehicles/h during diurnal peaks), these physical variables are delineated explicitly as concurrent spatial pressures rather than statistically validated causal drivers. Owing to the limited sample size (N = 26 independent encounters) and short-term observational framework, multivariable

Table 1: Frequency of primate encounters during six days of observation in the corridor

Species name	Observation day (OD)						Total
	OD1	OD2	OD3	OD4	OD5	OD6	
Hylobates 8ndone	6	4	2	4	0	3	19
Presbytis comata	3	0	0	0	1	0	4
Macaca fascicularis	0	0	0	0	3	0	3
Total per day	9	4	2	4	4	3	26

inferential models, including generalized linear mixed models and spatial occupancy regressions examining traffic volume, vehicle velocity, ambient noise levels, and gap structure relative to encounter rates, were omitted to preclude severe model overfitting. A key limitation of the present study design is the absence of a paired interior control site, continuous acoustic logging, vehicle speed sampling, and multivariate spatial occupancy modeling. Consequently, the manuscript does not demonstrate that reported traffic volume directly caused the observed avoidance or movement restriction. Rather than providing inferential proof of road-induced behavioral modification, the physical gap metrics and vehicular traffic counts documented herein function as descriptive baseline parameters intended to locate structural bottlenecks for engineering intervention. The dual-zone canopy bridge design presented herein directly targets physical structural connectivity across the 12–28 m canopy gaps. While restoring structural continuity is a necessary prerequisite to facilitate functional connectivity (physical crossing behavior), any downstream benefits to demographic stability or genetic connectivity remain prospective hypotheses that cannot be demonstrated without post-installation genetic monitoring. Instead of evidencing definitive behavioral mechanisms like intentional road avoidance or ecological bottlenecking, the spatial arrangement of primate sightings reflects a localized reduction in encounter frequency. While encounter rates for *Presbytis comata* and *Macaca fascicularis* were lower near the road edge relative to *Hylobates moloch*, these observational data cannot isolate road proximity or vehicular presence as the sole driver. Furthermore, alternative ecological and methodological confounders, including microhabitat variation, localized resource availability (e.g., fruiting phenology), baseline home range configurations, vertical detectability gradients across canopy strata, seasonal behavioral shifts, and inherent spatial heterogeneity—were not systematically quantified within this short-term survey and thus cannot be entirely ruled out. Consequently, the persistence of *Hylobates moloch* sightings near canopy gaps should be interpreted strictly as an observational baseline of spatial presence during the sampling period rather than an indicator of behavioral entrapment or road tolerance. Longitudinal surveys integrate vegetation structure mapping, phenological tracking, distance sampling for detectability correction, and individual movement tracking to decouple authentic behavioral responses from natural spatial heterogeneity.

Dual-zone canopy bridge engineering design

To accommodate the distinct locomotor mechanics of sympatric primates while avoiding premature specification of unmeasured physical dimensions, the proposed architecture categorizes crossing structures into two functional zones. Zone 1 (6-8 m height) has a flexible suspended walkway that is made for Presbytis comata and Macaca fascicularis to climb and jump on all fours. The dimensions of the mid-canopy gap (12-18 m) match those of the walkway. Zone 2 (15-20 m height) proposes a rigid structural frame to minimize horizontal oscillation during high-momentum ricochetal brachiation by *Hylobates moloch* across wider upper-canopy gaps (20-28 m). Because precise structural dimensions, such as support column diameters, steel pipe wall

thicknesses, and anchor plate specifications, depend on comprehensive static and dynamic load modeling, the material recommendations outlined here serve strictly as qualitative design guidelines. Rigorous engineering calculations assessing dynamic impulse loads, generated by brachiating fauna (10-15 kg body mass exerting multi-G acceleration forces) alongside extreme wind shear across open rights-of-way constitute vital prerequisites for physical fabrication. The dual-zone canopy bridge framework synthesized in this study represents an empirical design proposal tailored to the spatial gap dimensions and locomotion biomechanics of sympatric primates along the corridor. Rather than representing a fully realized or structurally tested engineering installation, the dual-zone framework functions as a conceptual structural blueprint derived from spatial gap geometry and primate locomotor biomechanics. Because formal mechanical stress calculations, wind-load modeling, safety factors, and anchoring tree stability assessments were not performed, the proposed material specifications (e.g., high-tensile synthetic ropes and rigid aluminum/composite cross-frames) remain theoretical recommendations. Pre-installation phases necessitates comprehensive structural analyses to determine dynamic load thresholds generated by canopy-dwelling fauna and extreme weather phenomena. Because no physical crossing structures were installed or experimentally evaluated during this sampling period, the proposed engineering parameters represent hypothesized mitigation strategies rather than empirically proven conservation outcomes. Rather than claiming that the system definitively restores connectivity, the rigid frame bridge (Zone 2) is designed to minimize structural oscillation and is expected to accommodate the upper-canopy brachiation mechanics of *Hylobates moloch*. Similarly, the suspended walkway (Zone 1) is hypothesized to provide a stable pathway for quadrupedal species *Presbytis comata* and *Macaca fascicularis*. Anticipated ecological benefits, such as reduced edge avoidance, restored gene flow, and long-term population persistence, remain prospective hypotheses that require empirical verification through post-construction monitoring. The pronounced reduction in primate occurrence along the transect suggests that the roadway functions primarily as a high-resistance barrier rather than a functional ecological transition zone (Andrasi *et al*., 2021). The absolute dominance of *Hylobates moloch* sightings over other sympatric primates reflects fundamental differences in evolutionary locomotion strategies and spatial niche flexibility under anthropogenic stress (Praill *et al*., 2023). As arboreal frugivores, *Hylobates moloch* display extreme territoriality and strict reliance on upper-canopy pathways (Atsaury *et al*., 2025). Their persistent presence near the roadway reflects ecological entrapment rather than behavioral tolerance; specialized morpho-anatomy precludes efficient terrestrial locomotion, compelling residual groups to occupy suboptimal habitats adjacent to canopy gaps despite ongoing disturbances. Conversely, the near-total absence of the *Presbytis comata* and the *Macaca fascicularis* highlights a pronounced avoidance response (Barbosa, 2024). While macaques generally exhibit behavioral plasticity in human-modified landscapes, the intense vehicular flux and structural degradation along this specific route appear to exceed their threshold of behavioral tolerance, driving them deeper into interior forest patches (Ascensão *et al*., 2022). Framed within landscape ecology, this localized spatial depletion shifts the function of the corridor from a biological to a demographic sink. The restriction of movement across linear infrastructure limits social group interactions, inhibits subadult natal dispersal, and suppresses natural seed dispersal networks critical for tropical forest regeneration (Liu *et al*., 2025). Over successive generations, severe spatial isolation restricts genes flow, elevates the threat of inbreeding depression, and substantially heightens the likelihood of localized extirpation.

These findings confirm that natural forest succession alone is insufficient to maintain functional connectivity, emphasizing the necessity of targeted structural interventions that accommodate species-specific canopy requirements (Amano *et al*., 2021). To evaluate the long-term ecological trajectory of the corridor, population metrics from 2025 were compared with historical baseline datasets established within the same national park by the Lembaga Ilmu Pengetahuan Indonesia (LIPI-JICA, 2004), as illustrated in Table 2 and Fig. 2. This historical comparison reveals a catastrophic, species-wide population density collapse exceeding 95%: 95.19% reduction for *Hylobates moloc* (from 2.370 to 0.114 ind/ha), 98.08% for *Presbytis comata* (from 1.250 to 0.024 ind/ha), and 97.95% for *Macaca fascicularis* (from 0.877 to 0.018 ind/ha). As detailed in Table 2, transect census data reveal substantial variation in population densities among the three endemic primate species across the fragmented forest patches of the Halimun Salak corridor. The *Hylobates moloch* recorded the lowest population density at 0.005 ind/ha, reflecting its high sensitivity to fragmentation and reliance on continuous upper-canopy structures.

In contrast, *Presbytis comata* and *Macaca fascicularis* exhibited higher estimated population densities of 0.024 ind/ha and 0.018 ind/ha, respectively. These spatial density gradients underscore the varying capacity of individual taxa to exploit secondary forest remnants and lower canopy strata within the road-edge zone. The profound population collapse documented in this study underscores that the HSMNP corridor has undergone severe functional degradation, converting a once continuous biological passage into a high-risk ecological sink (Yang *et al*., 2025; Widyastuti *et al*., 2023). The 3-km road operates as a persistent physical and behavioral barrier. Continuous canopy clearance clearing for road maintenance widens structural gap widths beyond the natural leaping capacity of non-brachiating species, whereas high-intensity vehicular noise elicits distinct avoidance behavior (Galea and Humle, 2022). The pronounced reduction in *Hylobates moloch* density is acutely concerning; as primary frugivores and seed dispersers, the attrition of functional gibbon home ranges along corridor edges disrupts rainforest succession and plant recruitment networks. Passive conservation or natural forest regeneration is insufficient to counteract this decline, as forest succession occurs too slowly relative to the rapid genetic depletion in isolated social groups (Atsaury *et al*., 2025). Beyond immediate spatial displacement, this multi-decadal population collapse poses critical consequences for the long-term genetic health and evolutionary trajectory of these sympatric primates' assemblages (Pandey *et al*., 2025; Nijman *et al*., 2019). The near-total elimination of individuals along the linear corridor restricts subadult natal dispersal, functionally transforming formerly continuous metapopulations into genetically isolated, small-scale subpopulations. As generations pass, severe habitat fragmentation accelerates genetic drift and impedes allele exchange across roadway barriers, thereby substantially heightening the vulnerability to inbreeding depression. For slow-reproducing, long-lived species like *Hylobates moloch* and *Presbytis comata*, this demographic bottleneck drastically reduces adaptive capacity to emerging environmental stressors and climate anomalies, greatly accelerating the probability of localized extirpation within the HSMNP edge zones. From a conservation and management standpoint, these results indicate that conventional passive protection policies are fundamentally insufficient to reverse multi-decadal population declines. The severity of the document collapse (> 95% decline) confirms that, without active structural intervention, ongoing degradation will permanently convert the corridor into a barrier to wildlife movement. To avert complete ecological fragmentation, immediate priority must be assigned to artificial green infrastructure, such as species-specific canopy bridges tailored to the distinct biomechanical

Table 2: Comparison of primate population density (2004 vs. 2025)

Species name	2004 primate population density (ind/ha)	2025 primate population density (ind/ha)	Decline rate (%)
Hylobates 11ndone	2.37	0.114	-95.19
Presbytis comata	1.25	0.024	-98.08
Macaca fascicularis	0.877	0.018	-97.95

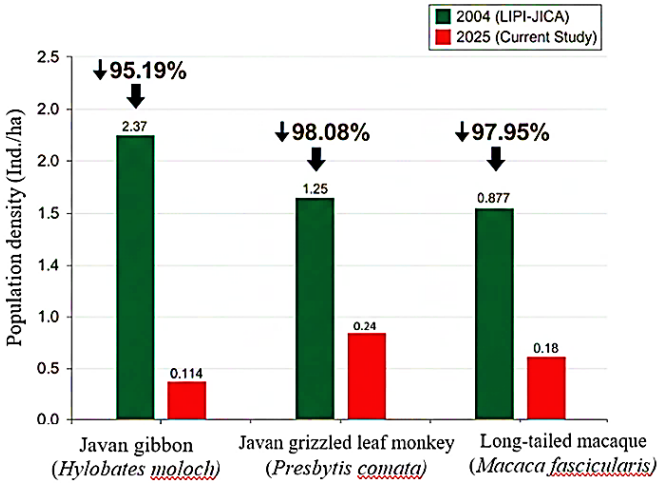

Fig. 2: Comparison of primate population density in HSMNP in 2004 vs. 2025

demands of brachiators and quadrupedal climbers. Re-establishing structural canopy connectivity, coupled with traffic-calming interventions and sensory disturbance filtration, represents an essential pathway for restoring functional gene flow, mitigating roadkill, risks, and halting the ongoing degradation of this critical conservation landscape.

Vertical stratification and locomotion biomechanics

Field observations demonstrated distinct vertical niche differentiation among the three primate species along the road corridor, as presented in Table 3. The *Hylobates moloch* exclusively utilized the upper canopy strata (10–20 m height, with peak sightings concentrated at 10–15 m), driven by its specialized ricochetal brachiation locomotion mode. In contrast, the *Presbytis comat* and *Macaca fascicularis* exhibited primary activity in the middle-to-lower canopy strata (5–10 m height), utilizing quadrupedal climbing, leaping, and occasional terrestrial foraging. The monitored primate social units exhibited intact family compositions, typically comprising 1–2 adults, 1 subadult, and 1 juvenile, suggesting that reproductive groups endure near the roadside despite encountering severe mobility restrictions. The spatial vulnerability of each species is intrinsically linked to its locomotion biomechanics and stratum preference. Because the *Hylobates moloch* depends entirely on contiguous upper-canopy branches for hand-over-hand brachiation, canopy gaps exceeding 5 m represent absolute movement barriers, effectively preventing ground crossings due to morpho-anatomical constraints (Simokar *et al*., 2025; Hankinson *et al*., 2021). Consequently, they are restricted to a single remaining natural point across the entire 3-km road stretch. Conversely, while Surilis and macaques exhibit superior gap-crossing capabilities across mid-canopy gaps, frequent vehicular traffic induces acute behavioral aversion, confining *Presbytis comata* to absolute structural isolation (Istiadi *et al*., 2024). When forced to negotiate ground-level crossings, subadults and juveniles experience disproportionately high vehicle collision risks and

Table 3: Frequency of tree height utilization by primate species in the HSMNP corridor

Species name	Tree height (m)					
	0-5 m	5-10 m	10-15 m	15-20 m	20-25 m	> 25 m
Hylobates 12ndone	-	1	15	3	-	-
Presbytis comata	-	2	-	-	-	-
Macaca fascicularis	-	3	-	-	-	-

predation threats, destabilizing multi-generational group dynamics (Torres-Romero *et al.*, 2023). The close integration of canopy height preference, locomotor mechanics, and micro-habitat utilization elucidates why linear canopy gaps function as selective filters on primate movement. The complete absence of *Hylobates moloch* in lower strata (< 10 m) highlights a strict biomechanical specialization, where branch compliance and terminal elasticity in upper canopies are essential to conserving energy during ricochetal brachiation. When roadway construction disrupts these continuous upper-canopy corridors, arboreal species are left functionally immobile; their elongated forelimbs and vestigial thumbs render ground-level locomotion both energetically demanding and biomechanically inefficient. On the other hand, the *Presbytis comata* and *Macaca fascicularis* can move around on all fours and jump, which lets them use the middle-to-lower strata (5–10 m). However, this places them in close proximity to vehicular traffic alongside visual and acoustic disturbances. Such spatial confinement intensifies sensory stress, eliciting pronounced behavioral avoidance that further impedes their movement, even across narrow canopy gaps. Consequently, effective mitigation cannot rely on a uniform structural design; rather, it necessitates multi-tiered crossing solutions tailored explicitly to the unique biomechanical capacities and vertical stratum preferences of each sympatric species.

Traffic dynamics and sensory disturbance filtration

Quantification of traffic intensity along the 3-km corridor revealed intense, uninterrupted human activity. As outlined in Table 4, daily vehicular counts ranged between 700 and 1,000 units, with a peak cumulative total of 1,234 vehicles observed during intensive monitoring. Two-wheeled motor vehicles dominated the traffic composition (85.5%), followed by passenger cars (11.1%), light trucks (3.1%), and buses (0.3%). Daytime traffic volume remained relatively stable, averaging approximately 100 vehicles per hour, with distinct peak intervals occurring between 10:00 and 11:00 AM (115 vehicles per hour) and 12:00 to 1:00 PM (111 vehicles per hour), as depicted in Fig. 3. The temporal overlap between peak human vehicular traffic and diurnal primate activity generates a severe ecological consequence (Entezami *et al.*, 2024; Kok *et al.*, 2023). Diurnal primates initiate foraging and territorial patrols between 06:00 AM and 13:00 PM, a time window that directly overlaps with vehicular flux (~115 vehicles/h). The acoustic profile generated by high-density motorcycle traffic (85.5%), distinguished by high-frequency exhaust emissions and abrupt shifts in pitch—acts as a persistent sensory barrier (Seiler and Bhardwaj, 2020). Acoustic disturbance impedes the perception of primate alarm calls, elevates systemic glucocorticoid levels, and provokes panic-flight reactions directed away from the roadside edge (Dittus *et al.*, 2021; Dasoler *et al.*, 2026). Consequently, traffic acts as a non-physical "sensory filter," converting a 3-to-4-meter asphalt strip into a functional barrier multiple times wider than its physical size (Tomchuk *et al.*, 2026). The non-physical nature of this "sensory filter" ecologically broadens the influence of the roadway well beyond its physical 3-to-4-m asphalt boundary, establishing a substantial road-effect zone. The acoustic environment vital to arboreal primates is disrupted by high-frequency exhaust emissions and erratic sound spikes from dense motorcycle traffic, which effectively obscures long-distance vocalizations, territorial duets, and social alarm signals (Galea and Humle, 2022). For vocal-dependent species like *Hylobates moloc*, this

Table 4. Hourly and daily vehicle traffic frequency in the HSMNP corridor

Time	Vehicle type				Total
	Truck	Bus	Car	Motorcycle	
06.00 – 07.00	2	0	3	92	97
07.00 – 08.00	4	0	11	90	105
08.00 – 09.00	6	0	6	91	103
09.00 – 10.00	1	1	7	94	103
10.00 – 11.00	3	0	12	100	115
11.00 – 12.00	1	1	4	92	98
12.00 – 13.00	2	0	10	99	111
13.00 – 14.00	4	0	7	98	109
14.00 – 15.00	1	0	6	91	98
15.00 – 16.00	2	1	7	92	102
16.00 – 17.00	3	0	14	94	111
17.00 – 18.00	2	0	4	76	82
Total	31	3	91	1109	1234

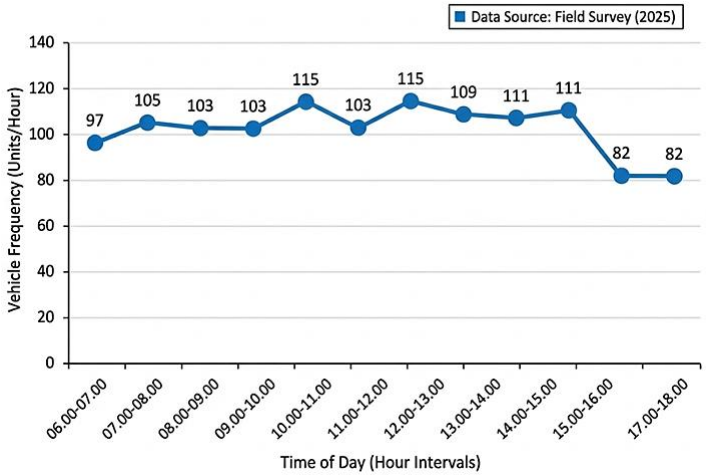

Fig. 3: Temporal distribution of vehicle frequency at the HSMNP corridor

auditory masking impairs intragroup communication and territorial defense, forcing groups to retreat deeper into the forest interior to maintain social cohesion. Furthermore, chronic exposure to loud, unpredictable vehicular noise elicits heightened physiological stress. This persistent strain elevates cortisol concentrations, culminating in immunosuppression, diminished reproductive success, and behavioral modifications in daily movement patterns among arboreal primates. As a result, these physiological disturbances diminish the long-term ecological carrying capacity of the fragmented forest habitat. The direct temporal overlap between peak diurnal traffic (10:00–11:00 AM and 12:00–13:00 PM) and the essential foraging and resting of sympatric primates severely reduces quality along the corridor. During these critical midday intervals, elevated disturbance levels force primates to trade energy intake for vigilance and avoidance behaviors, thereby curtailing efficient foraging along food- abundant canopy margins (Terray *et al.*, 2025). This perpetual disruption creates a behavioral avoidance zone along the road margin. Consequently, effective mitigation protocols along the HSMNP corridor must transcend physical canopy crossings to integrate sensory abatement measures, including velocity restrictions, acoustic-absorbing pavements, and vegetated buffer zones—thereby shrinking the road-effect zone and reinstating functional dispersal corridors across the landscape.

Environmental engineering mitigation framework

To address the observed movement barrier and canopy gaps, an integrated dual-zone artificial canopy bridge system was formulated as a proposed engineering mitigation model. Rather than assessing post-implementation structure, these technical designs (Zone 1 and Zone 2) constitute site-specific structural interventions focused on empirically validated encounter hotspots and aligned with the unique locomotor mechanics of the target species. To resolve the structural barrier effect and provide an immediate, non-invasive corridor linkage, an integrated dual-zone artificial canopy bridge was engineered as a mitigation strategy based on spatial migration density mapping (Fig. 4). Two primary high-priority crossing zones were identified along the three-kilometer road stretch based on encounter cluster spatial analysis, with complete structural and spatial parameters detailed in Table 5:

1. Multi-taxa and semi-arboreal migration zone (distance 1,200 to 1,300 meters): Positioned at an elevation of 800 *m.a.s.l.*, this zone meets the movement needs of the *Presbytis comata*, *Macaca fascicularis*, and small arboreal mammals. The structural design incorporates an eight-meter-wide mesh-type suspended walkway spanning twelve meter roadway, positioned at a clearance height of six to eight meters (Fig. 5 and Table 5). The structural framework incorporates five-inch-diameter galvanized steel pipe supports, ensuring high torsional rigidity and multi-point anchorage to accommodate concurrent multi-taxa movement within their preferred mid-canopy stratum (five to ten meters).
2. Upper-canopy brachiator migration zone (distance 800 to 900 meters): Located at an elevation of 900 *m.a.s.l.*, this specialized installation is engineered exclusively for *Hylobates moloch*. To accommodate the specialized brachiating locomotion of this species, the structure comprises a rigid, 15- to 20-meter-high structural steel frame bridge spanning ten meters across the canopy gap (Fig. 6; Table 5). Constructed with ten-inch-diameter heavy-duty steel pipe columns and high-tensile flexible cables, this bridge corresponds to the natural upper-canopy height preference (10 to 20 meters), dampens wind-induced oscillation, and supplies the structural rigidity necessary for brachiation mechanics.
3. As summarized in Table 5, the structural differentiation between Zone 1 and Zone 2 directly corresponds to the biomechanical and behavioral constraints of the respective target species. Single-rope or simple canopy bridges frequently fail for specialized brachiators like *Hylobates moloch* due to high lateral sway and mechanical instability (Chan *et al*., 2020). The deployment of a heavy-duty ten-inch steel pipe configuration featuring a 15 to 20-meter clearance height, spaced 800 to 900 meters apart, provides the requisite torsional rigidity to suppress wind-driven oscillation, while aligning with the upper-canopy preference and dynamic momentum characteristic of gibbon brachiation (Mitchell *et al*., 2022).

Conversely, the eight-meter-wide suspended walkway in Zone 1 (distance 1,200 to 1,300 meters) provides a broader, highly stable substrate that accommodates the quadrupedal walking and leaping movements of the *Presbytis comata* and *Macaca fascicularis* (Table 5). Implementation of this dual-zone engineering framework establishes a permanent vertical buffer, effectively separating biological migration routes from ground-level anthropogenic activities (representing approximately 2,000 daily human users) (Birot *et al*., 2020; Galea and Humle, 2022). Installing these engineered structures directly at empirically verified encounter hotspots avoids trial-and-error placement, delivering an

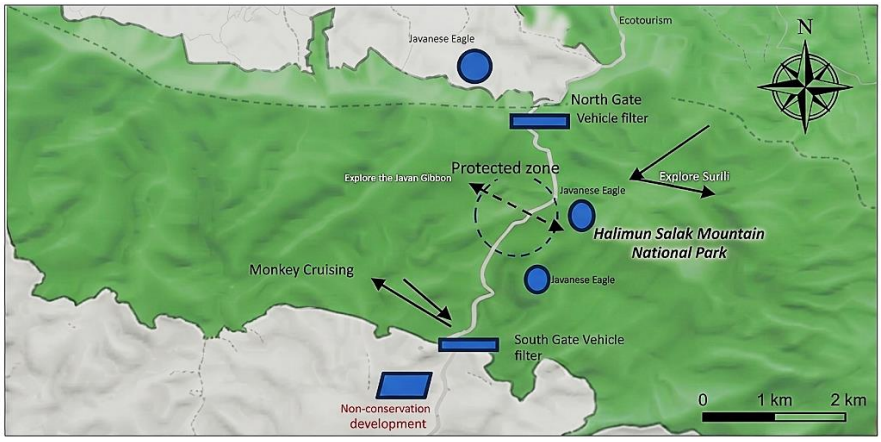

Fig. 4: Spatial distribution of primate encounters (N = 26) and physical canopy gaps along the 3,000-m road corridor, illustrating proposed target placement zones for Zone 1 (1,200-1,300 m) and Zone 2 (800-900 m). Note: These locations represent targeted preliminary priority sites derived from spatial encounter overlap and gap geometry, rather than mathematically optimized crossing locations



Fig. 5: Technical proposal for a crossing bridge dedicated to the *Presbytis comata* and small mammals at the 1,200 m mark

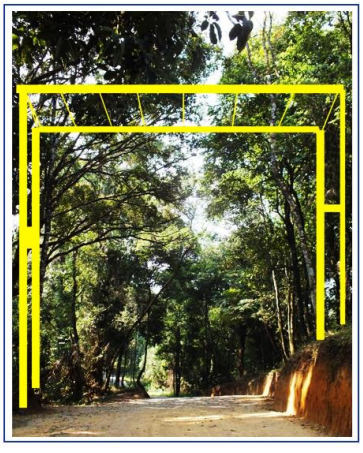

Fig. 6: Technical proposal for the *Hylobates moloch* crossing bridge at the 900-meter mark, the design features a clearance height of 15–20 meters, integrated with upper canopy strata

Table 5. Technical specifications and spatial zoning for the proposed artificial canopy bridge mitigation system in HSMNP

Zone/location	Target species	Strata preference and locomotion mode	Elevation (m. a. s. l.)	Crossing clearance height (m)	Structural framework specifications	Primary engineering function
Zone 1 (Distance 1,200–1,300 m)	*Presbytis comata*, *Macaca fascicularis*, and small arboreal mammals.	Mid-to-lower canopy (5–10 m); quadrupedal climbing and leaping.	800	6–8	5-inch galvanized pipe frame; 8-m wide suspended walkway spanning 12 m.	Facilitates multi-taxa terrestrial and semi-arboreal migration; high multi-point anchorage.
Zone 2 (Distance 800–900 m).	*Hylobates 16moloch*	Upper canopy (10–20 m); ricochetal brachiation.	900.	15–20.	10-inch heavy-duty pipe support columns; 10-m span rigid frame bridge.	Provides high torsional rigidity to withstand wind oscillation; matches upper-canopy brachiation mechanics.

immediate, non-invasive corridor connection while natural canopy restoration proceeds along riparian buffer zones (Balbuena *et al*., 2019; Situmorang and Noviana, 2025). Ultimately, this ecological engineering application acts as a scalable technical model to halt genetic isolation and re-establish functional connectivity for endangered arboreal primates across fragmented tropical ecosystems (Chan *et al*., 2020). The strategic differentiation between Zone 1 and Zone 2 structural designs addresses the mechanical limitations that cause conventional single-rope canopy crossings to fail for large-bodied or biomechanically specialized arboreal fauna. Obligate brachiators like the Javan gibbon (*Hylobates moloc*) require structural rigidity to absorb dynamic momentum and pendulum forces during high-speed ricochetal locomotion; excessive lateral sway or vertical oscillation can provoke behavioral rejection, confining individuals within isolated canopy fragments. By utilizing 10-inch heavy-duty steel support columns at a 15–20-meter clearance height within Zone 2, the bridge supplies the requisite torsional stability and vertical elevation to emulate natural upper-canopy pathways. In contrast, the 8-meter-wide suspended ladder walkway in Zone 1 accommodates the broader foot placement and group-crossing behaviors of quadrupedal species *Presbytis comata* and *Macaca fascicularis*, enabling simultaneous multi-taxa movement while reducing visual contact with passing ground traffic (Ceia-Hasse *et al*., 2024; Praill *et al*., 2023). Positioning these engineered crossing structures precisely at empirically identified encounter hotspots (at intervals of 800–900 m and distance 1,200–1,300 m) optimizes intervention efficiency by targeting established spatial movement routes rather than relying on arbitrary placement. Bridging these primary canopy gaps bypasses the multi-decadal time lag required for natural rainforest restoration, offering an immediate physical conduit that reconnects fragmented home ranges (Birot *et al*., 2020; Hewlett *et al*., 2024). Beyond functioning merely as a physical connection, this green infrastructure framework establishes a functional vertical buffer zone that insulates wildlife transit from ground-level anthropogenic pressures, including vehicular collision hazards, noise-pollution, and unauthorized human intrusion. When integrated with long-term habitat enrichment along riparian buffer zones, this dual-zone technical framework offers a scalable, adaptable template for biodiversity conservation and landscape-level connectivity restoration across infrastructure-impacted tropical ecosystems (Yamashita *et al*., 2024; Balbuena *et al*., 2019). Ultimately, the acute population contraction exceeding 95% among endemic primates in the HSMNP corridor illustrates that road-induced canopy fragmentation functions as both a physical and

sensory barrier to wildlife movement. The direct temporal overlap between diurnal primate foraging schedules and peak traffic volume (~100 vehicles/h) underscores the inadequacy of passive conservation measures. By synchronizing structural engineering parameters with empirical locomotion biomechanics and spatial encounter hot spots, the proposed dual-zone artificial canopy bridge system is designed to mitigate ground-level anthropogenic disturbance. This green engineering framework supplies an immediate, scalable, and non-invasive technical intervention designed to reinstate vertical canopy connectivity, prevent genetic isolation, and secure the long-term persistence of threatened arboreal primates within human-dominated tropical rainforest landscapes. A primary limitation of this study is its reliance on a six-day diurnal monitoring dataset to establish baseline primate presence along the corridor. Consequently, the proposed dual-zone bridge system serves as a baseline engineering prototype; long-term post-installation monitoring using continuous camera-trap arrays is essential to evaluate actual wildlife habituation, crossing frequency, and overall structural performance and ecological effectiveness over time.

CONCLUSION

Linear infrastructure development across tropical rainforest ecosystems creates spatial barriers that disrupt canopy continuity. Arboreal primates, such as the endangered *Hylobates 17moloch*, are highly vulnerable to these anthropogenic effects due to their strict reliance on upper-canopy strata for locomotion, foraging, and social interaction. Standard single-rope crossing structures frequently fail to accommodate species-specific biomechanical requirements and omit physical disturbance mitigation, precipitating pronounced spatial avoidance along active transport corridors. This study evaluated the structural and ecological parameters required to re-establish vertical connectivity across fragmented forest corridors, providing an empirical baseline assessment of canopy discontinuity and primate distribution along a high-risk transportation route. While current local primate densities along the road (0.114 ind/ha for *Hylobates moloch*, 0.024 ind/ha for *Presbytis comata*, and 0.018 ind/ha for *Macaca fascicularis)* are substantially lower park-wide baseline averages, this observational study does not establish direct causality between traffic parameters and population trends, nor are these metrics extrapolated to the broader 15,000-ha national park landscape. The physical gap dimensions and encounter coordinates documented herein function strictly as baseline spatial parameters to guide canopy bridge placement, furnishing a pragmatic engineering framework for restoring ecological connectivity. Field assessments and engineering demonstrated that traditional single-strand rope bridges exhibit excessive elasticity, inducing behavioral hesitation in brachiating primates. To address these limitations, a dual-zone structural framework was synthesized: Zone 1a (a 6-8-meter-high suspended-type walkway at a distance 1,200-1,300 m) accommodates quadrupedal climbing and leaping for *Presbytis comata* and *Macaca fascicularis,* while Zone 2 (a 15-20-meter-high rigid structural frame bridge at a distance 800–900 m) provides high torsional stability to match the upper-canopy ricochetal brachiation mechanics of the *Hylobates moloch*. Active ecological engineering through dual-zone canopy bridge frameworks presents a robust approach for reinstating canopy continuity across fragmented landscapes. By synchronizing structural engineering parameters with the behavioral ecology and locomotion mechanics of arboreal fauna, this multi-tiered framework suppresses structural instability and reinstates natural transit across anthropogenic gaps. While this framework supplies a structurally validated mitigation proposal, its current scope is constrained by short-term observational data, the absence of an interior control site, and a lack of systematic acoustic monitoring (dBA) or multivariable statistical modeling directly linking traffic volume and canopy gaps to primate density. Subsequent

studies must integrate control-impact monitoring designs, long-term camera-trap arrays, calibrated acoustic monitoring, and multivariate regression models to empirically isolate the drivers of road avoidance, evaluate post-installation species habituation rates, quantify genetic restoration, and assess the long-term structural integrity of bridge materials over extended operational lifespans. Because empirical genetic sampling and dispersal tracking were not conducted, assertions concerning the restoration of genetic connectivity, enhanced gene flow, and long-term population persistence constitute projected benefits rather than demonstrated outcomes. Although the proposed dual-zone framework establishes an ex-ante design to re-establish structural connectivity; subsequent empirical research must determine whether this structural intervention successfully achieves functional connectivity (using continuous camera-trap arrays) and long-term genetic connectivity (via non-invasive fecal DNA sampling and parentage analyses).

AUTHOR CONTRIBUTIONS

M.T.S. Situmorang, conceptualized the research framework, designed the field sampling protocols, conducted ecological and traffic data collection, performed spatial density, drafted the original manuscript, and synthesized the environmental engineering mitigation strategy. B. Hasibuan, supervised the field investigation, validated the locomotion biomechanics and population density calculations, contributed to the structural bridge design specifications, critically reviewed and edited the manuscript draft, and provided administrative and funding support. Both authors read and approved the final of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancy, have been completely observed by the authors.

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expression, structural flow, and grammatical accuracy of the text. After using this tool or service, the authors reviewed and edited the content as needed and took full responsibility for the publication.

ABBREVIATIONS

%	Percent
asl	Above sea level
E	East
CI	Confidence intervals
GIS	Geographic information system
ha	Hectare
HSMNP	Halimun salak mountain national park
ind/km	individuals per kilometer
ind/ha	Individuals per hectare
IUCN	International Union for Conservation of Nature
JICA	Japan international cooperation agency
km	Kilometer
km/h	Kilometers per hour
LPPM	Lembaga penelitian dan pengabdian masyarakat (Research and community service)
LIPI	*Lembaga ilmu pengetahuan 19ndonesia* (Indonesian Institute of sciences)
LTI	Laser technology, inc
m	Meters
m.a.s.l.	Meters above sea level
MaxEnt	Maximum entropy
OD	Observation day
S	South
vehicle/h	Vehicles per hour
Vs.	Versus

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