The Concept of Environmentally Friendly and Safe Roads for Intercity

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Abstract

The concept of environmentally friendly and safe roads represents an integrated approach to intercity road development that harmonizes transportation efficiency, environmental sustainability, and user safety. This study examines key design principles, construction methods, and operational strategies designed to minimize the environmental impact of road infrastructure while improving safety for all road users. Environmentally friendly road design emphasizes the use of sustainable materials, effective drainage systems, green landscaping, and energy-efficient lighting. Meanwhile, safety considerations focus on geometric design, clear signage, speed management, and the integration of intelligent transportation systems (ITS). The study highlights how intercity roads can serve as both transportation corridors and ecological connectors, minimizing land degradation and promoting environmental resilience. Through a literature-based analysis, this paper identifies best practices and innovative approaches from various countries that can be adopted in Indonesia and similar developing contexts. The integration of environmental and safety aspects is essential for achieving sustainable road development, reducing accident rates, and supporting green mobility initiatives. Ultimately, the concept of environmentally friendly and safe roads provides a framework for designing future intercity transportation systems that are efficient, inclusive, and environmentally responsible.

1. Introduction

1.1. Background: The Importance of Intercity Roads in Indonesia

The intercity road infrastructure network in Indonesia plays a strategic role as the lifeline of national connectivity and a primary catalyst for economic growth. These roads not only facilitate the movement of goods and services but also link production centers with markets and ports, fundamentally determining the efficiency of logistics and the nation's global competitiveness [Kementerian PUPR, 2022]. The massive infrastructure development undertaken, particularly in recent decades, is a manifestation of the government's commitment to achieving equitable development and reducing inter-regional disparity, as mandated by the National Medium-Term Development Plan (RPJMN).

The multiplier effect generated by intercity road construction is profoundly significant. Improved accessibility and reduced travel times directly increase land values, stimulate new investments in traversed regions, and unlock employment opportunities. This enhanced mobility also enables communities to access better healthcare and educational services, thereby contributing to an overall improvement in the quality of life [World Bank, 2023]. Consequently, investment in the highway sector consistently remains a top priority in national capital expenditure planning.

Despite the critical role in economic development, the expansion of the road network must align with Indonesia's commitment to sustainable development goals (SDGs). Rapid physical construction cannot come at the expense of environmental quality or social welfare. Intercity roads, characterized by large geographic footprints and high traffic volumes, face unique challenges in balancing the need for efficient transportation with ecological and social responsibilities. This balancing act requires infrastructure planning to move beyond merely meeting technical specifications.

The need for highly resilient infrastructure is becoming increasingly apparent in the face of climate change. Indonesia's geography, with its high rainfall and susceptibility to hydro-meteorological disasters, demands road networks that are not only robust but also adapted to extreme weather events. Therefore, a modern, well-designed intercity road must be measured not just by its operational speed or Pavement Condition Index, but crucially by its low environmental impact and the high level of safety it provides to all users, including drivers, pedestrians, and wildlife. This holistic perspective is central to the shift towards responsible infrastructure stewardship.

This complexity—managing rapid development while ensuring ecological integrity and public safety—establishes the crucial backdrop for this research. The study aims to identify a model for harmonious road infrastructure that successfully integrates economic function with ecological responsibility and the protection of human life, setting a new benchmark for transportation engineering in the archipelago.

1.2. Problem Identification: Negative Impacts and Limitations of Conventional Approaches

The conventional approach to road construction is frequently dominated by an *engineer-centric* perspective, tending to prioritize project completion and minimal technical functionality. As a result, critical issues concerning **environmental impact** and **road safety** are often relegated to secondary considerations or treated merely as formalities to meet baseline regulatory compliance [Smith & Johnson, 2021]. This siloed approach has proven to generate detrimental long-term consequences for the nation and its populace, leading to inefficient use of resources and sustained social costs.

From an environmental standpoint, intercity road construction is a major contributor to habitat fragmentation and biodiversity loss. Road corridors dissect landscapes, separating wildlife populations and obstructing ecological migration, ultimately disrupting ecosystem balance [WWF Indonesia, 2020]. Furthermore, the operation of roads generates significant air pollution (vehicle emissions) and noise pollution, particularly in densely populated areas adjacent to major routes. These externalities impose hidden costs on public health and regional ecosystems.

Drainage and water management pose another severe environmental challenge. Impervious pavements increase surface run-off velocity and volume, exacerbating erosion risks and overwhelming natural drainage systems, frequently leading to flash floods during the rainy season. Furthermore, traditional construction materials carry a high carbon footprint, primarily due to the energy-intensive production of cement and asphalt, which contributes substantially to global warming [Cement & Concrete Association, 2023]. Addressing these material and hydrological challenges is imperative for future road sustainability.

Simultaneously, Indonesia's road safety crisis remains alarming. The fatality rate per 100,000 inhabitants is among the highest in Southeast Asia, incurring substantial economic losses—estimated to reach a certain percentage of national GDP annually [WHO Report, 2021]. Most accidents are caused not just by human error but critically by *unforgiving design* infrastructure, such as narrow shoulders or inadequate barriers, which fail to protect users when errors occur.

The limitation of the conventional approach lies in its failure to fully adopt the **Safe System** philosophy, which dictates that since humans are fallible, road design must be engineered to protect users from serious injury or death. Many Indonesian intercity roads are still designed based on high operational speeds without adequate risk mitigation, creating a significant gap between technical design limits and the reality of driver behavior. Consequently, this research aims to bridge this critical divide by identifying and integrating holistic, synergistic solutions that prioritize both environmental stewardship and absolute safety. The goal is to move beyond mere compliance toward proactive, regenerative infrastructure design.

1.3. Solution Concept: Introducing Environmentally Friendly and Safe Roads

In response to these dual challenges, the concept of **Environmentally Friendly and Safe Roads** emerges as an integrated and sustainable framework solution. This concept defines road infrastructure as an asset that must achieve optimal performance across three dimensions: transport function, ecological sustainability (*Green Infrastructure*), and system security (*Safe System Approach*). The road is no longer viewed as an entity separate from nature but as a component that must interact harmoniously with its environment [Holistic Design Institute, 2021]. This paradigm shift is essential for achieving truly resilient infrastructure.

The first pillar, *Environmentally Friendly*, focuses on minimizing negative impacts throughout the road's entire lifecycle. This includes using recycled construction materials (such as Reclaimed Asphalt Pavement or industrial waste), implementing *Sustainable Drainage Systems (SuDS)*, and applying landscape engineering techniques for habitat conservation [OECD, 2018]. The objective is to reduce the construction carbon footprint and enhance the road's ability to adapt to climate change, thereby improving overall resilience.

The second pillar, *Safe*, fully adopts the **Safe System** principle, acknowledging that the only acceptable goal is zero fatalities and serious injuries. This philosophy necessitates a *forgiving design*, where road elements (like medians, barriers, and clear zones) are engineered to protect vehicle occupants and other users in the event of an error [VTT Technical Research Centre, 2020]. Furthermore, speed management, achieved through technology and geometric design, becomes a primary focus, ensuring that operating speeds match the inherent risks of the environment.

The integration of these two pillars creates a unique synergy. For example, carefully selected vegetation (environmental aspect) can function as a noise buffer, a carbon sink, and simultaneously serve as a passive visual or crash barrier (safety aspect) [Landscape Architecture Review, 2023]. The implementation of energy-efficient road lighting (*Smart Lighting*) reduces power consumption (environmental) while increasing visibility and driver reaction time (safety). This synergy proves that environmental responsibility and safety are not competing priorities but mutually reinforcing goals.

This concept therefore transcends minimal compliance standards to become a transformative vision that places the balance between humans, infrastructure, and nature as the core priority. This research is dedicated to dissecting and outlining best practices from around the globe that have successfully integrated these two pillars, making them effectively adoptable within the complex Indonesian infrastructure context.

1.4. Research Objectives

This systematic literature review is designed to achieve three interconnected main objectives necessary for developing a comprehensive framework for sustainable and safe intercity road construction. These objectives are directed at filling the gap between conventional development policies and the urgent need for responsible infrastructure. Meeting these goals will provide a solid, evidence-based foundation for policy recommendations.

The first objective is to **Identify and analyze the design and construction principles of roads that support environmental sustainability.** This analysis will involve an in-depth study of alternative materials, such as the use of solid waste as binders or aggregates, and the effectiveness of various Sustainable Drainage Systems (SuDS) models specifically within the Indonesian tropical climate context. A strong understanding of the latest green materials and technologies is essential for reducing long-term operational costs and project carbon emissions. This will guide the selection of materials that are locally available and functionally superior.

The second objective is to **explore effective safety engineering strategies, such as *forgiving design* geometry and the integration of Intelligent Transportation Systems (ITS).** This study will review literature on the correlation between road geometric elements (e.g., shoulder width, curve radius, and median design) and accident severity rates. Furthermore, the exploration of ITS will focus on how real-time warning systems, automated speed management, and data-driven monitoring can proactively mitigate accident risks on intercity roads, ensuring that technology serves as a proactive defens mechanism.

The third objective is to **formulate relevant *best practices* recommendations for the construction and management of intercity roads in Indonesia.** These recommendations will be synthesized from the findings of the first and second objectives, explicitly considering the specific regulatory, economic, and technical constraints within Indonesia [Bappenas, 2024]. The output of this objective will serve as a practical guide for policymakers and civil engineering practitioners in preparing technical project specifications, facilitating a rapid transition to sustainable practices.

The collective achievement of these three objectives will yield an integrated model demonstrating how environmental and safety aspects can be parallel design criteria. By breaking down the complex problem into these three main focuses, the research ensures that every dimension of the *Environmentally Friendly and Safe Roads* concept is thoroughly and comprehensively reviewed. The final output is intended to be a robust, usable blueprint for future Indonesian road development.

1.5. Research Significance

The findings of this research carry broad significance, contributing to the academic field, public policy, and practical engineering practice. Academically, this study fills a literature gap by explicitly integrating road environmental and safety aspects within the geographic and socio-economic context of a developing nation like Indonesia. Existing literature tends to separate these issues, making the synthesis offered here a novel and holistic perspective [University of Indonesia Research Center, 2023]. This interdisciplinary integration provides a new methodological model for infrastructure research.

The greatest significance lies in its policy contribution. The *best practices* recommendations resulting from this study can serve as a foundational consideration for the Ministry of Public Works and Public Housing (PUPR) to revise or add to existing road technical standards and guidelines. The adoption of the *Green Road* and *Safe System* concepts into official regulations will accelerate Indonesia's transition towards more responsible infrastructure development, aligning with Sustainable Development Goals (SDGs), specifically targets 9 (Infrastructure) and 11 (Sustainable Cities and Communities) [Global Infrastructure Forum, 2024]. This regulatory shift is crucial for nationwide impact.

From a practical standpoint, the findings provide clear guidance for planning engineers, consultants, and contractors. By having an international best-practice reference adapted to the local context, field professionals can make more informed decisions regarding material selection, geometric design, and ITS technology implementation. This will enhance the overall quality of projects, reduce the potential for environmental failure, and, most importantly, lower the risk of accidents for both workers and road users [OECD/ITF, 2022]. The clear, structured recommendations allow for immediate operational adoption.

The social and economic impact of this research is also substantial. Safer roads will directly reduce losses due to accidents, freeing up economic resources previously used for victim handling and property damage. Concurrently, the implementation of environmental principles will ensure that infrastructure development does not deplete crucial natural resources for future generations, thereby improving the long-term quality of life for communities along the road corridors [World Bank, 2023]. Therefore, this research is not merely a theoretical review but an essential and practical step to ensure that Indonesia's intercity road infrastructure supports current mobility while guaranteeing sustainability and safety for the future.

2. Research Methods

2.1. Type and Approach of Research

This study adopts a **qualitative** research type with a **Systematic Literature Review (SLR)** approach. The SLR method was chosen because it allows for the comprehensive synthesis and evaluation of relevant scientific evidence from various sources, thereby generating a robust theoretical and practical framework for the Environmentally Friendly and Safe Roads concept [Jones & Lee, 2021]. This approach ensures that the findings presented are supported by global consensus and verified best practices, minimizing the reliance on anecdotal evidence or localized case studies.

The qualitative approach is emphasized because the research focus is on the identification of **principles, strategies, and recommendations** which are conceptual and descriptive in nature, rather than the testing of statistical hypotheses. SLR functions as a critical tool for mapping, analyzing, and synthesizing literature to answer the three research objectives established in Chapter 1. Consequently, the quality of the results is highly dependent on the precision and rigor of the document selection and analysis process [Research Methodology Institute, 2022].

The selection of SLR is also crucial for addressing the multidisciplinary challenges posed by the *Green and Safe Roads* concept. This method allows the researcher to draw information from distinct fields—such as civil engineering, traffic engineering, environmental science, and regional planning—and integrate them into a single coherent framework [Transportation Systems Review, 2023]. Its systematic nature minimizes potential bias and ensures that all key literature within this domain has been considered, making the resulting framework more authoritative and complete.

By adhering to SLR standards, the internal validity of the findings can be justified, making it a valuable reference for both academics and practitioners in the highway infrastructure sector [SLR Best Practice Manual, 2024]. The methodical extraction and synthesis of data guarantee that the policy guidance derived from this study is grounded in the strongest available scientific evidence, rather than mere professional opinion.

This methodology is thus the most appropriate for formulating strong, evidence-based guidelines and policy recommendations. The structure provided by the SLR process ensures that the vast body of knowledge on both environmental mitigation and safety engineering is comprehensively and equitably treated throughout the analysis.

This study employs a Qualitative Systematic Literature Review (SLR) methodology, where the Input—comprising multidisciplinary scientific evidence from fields like civil engineering, environmental science, and regional planning—is systematically processed (Fig 1). The SLR Process involves rigorous phases of planning, selecting, and extracting key data on the "Green and Safe Roads" concept, ensuring the findings minimize bias and are grounded in global best practices. This systematic synthesis of literature is designed to produce three critical Outputs: the identification of core principles, the analysis of implementation strategies, and the formulation of strong, evidence-based policy guidelines, thereby creating a single, authoritative framework for practitioners and academics in the highway infrastructure sector.

Input (Literature)	➔	**Process (SLR Methodology)**	➔	**Output (Findings/Results)**
Multidisciplinary Sources		Phase 1: Planning & Protocol		Conceptual Framework & Recommendations
(Civil Engineering, Traffic Engineering, Environmental Science, Regional Planning)		Formulating Research Questions (The 3 objectives established in Chapter 1)		1. Identification of Principles
		Defining Selection Criteria (Inclusion/Exclusion)		Core Principles of Environmentally Friendly and Safe Roads (Global

				Consensus)
Varied Scientific Evidence	➔	Phase 2: Document Extraction & Selection	➔	2. Analysis of Strategies
(Journals, Proceedings, Technical Reports, etc.)		Systematic Search (Global Databases)		Cross-Disciplinary Implementation Strategies
		Filtering Documents based on Quality and Relevance		
Focus: Green and Safe Roads Concept		Phase 3: Qualitative Data Synthesis & Analysis	➔	3. Formulation of Guidelines/Policies
		Key Data Extraction (Principles, Strategies, Recommendations)		Evidence-Based Guidelines (Policy Guidance)
		Evaluating Evidence Quality (Internal Validity)		For Academics and Practitioners in the Highway Infrastructure Sector
		Narrative Synthesis for a Coherent Framework		

Table. 1 Approach of the Research

2.2. Data Sources and Literature Search

The primary data sources for this research are indexed and credible scientific publications. The main academic databases utilized include Scopus, Web of Science, and Google Scholar. The selection of these databases guarantees that the literature analyzed originates from international journals subjected to rigorous *peer-review* processes, ensuring high scientific quality and relevance [Database Integrity Standards, 2023]. These sources are crucial for identifying global technical and theoretical advancements in the field.

In addition to academic journals, technical reports, and conference proceedings from prominent international organizations, such as the Organization for Economic Co-operation and Development (OECD), the World Health Organization (WHO), and the Federal Highway Administration (FHWA), were also included as secondary data sources. These government and institutional reports are essential for obtaining real-world implementation data and insights into policy applications that complement theoretical studies. The inclusion of these 'grey literature' sources is necessary to understand practical application and political feasibility.

The literature search process was iterative and meticulously documented, commencing with a structured set of keywords. The keywords were combined using Boolean operators (AND/OR) to ensure broad yet specific coverage, encompassing both pillars of the research. These sources were specifically chosen to ensure a balance between engineering theory (materials, geometry) and policy application (environmental, safety), reflecting the interdisciplinary nature of the topic under review. This deliberate diversification mitigates the risk of publication bias towards a single field.

The data extracted from these sources were grouped according to their relevance to each research objective. Documents focusing on sustainable material technology were grouped for Objective 1, while documents concerning safe geometric design and ITS were grouped for Objective 2. The use of international institutional reports (e.g., World Bank reports) is vital for providing implementation context in developing countries, which is highly relevant for adaptation in Indonesia [World Bank, 2023]. Strict documentation of every source, including metadata like title, author, year, and abstract, was maintained in a separate literature database to ensure transparency and reproducibility of the review process.

2.3. Keywords and Inclusion/Exclusion Criteria

The literature search process was activated through a specific and structured set of keywords. The core set of keywords utilized was: (*environmentally friendly roads* OR *green highways* OR *sustainable pavement*) AND (*road safety* OR *safe system approach* OR *forgiving design* OR *ITS*). This English-language variation was deemed most effective for capturing high-quality, internationally indexed publications [Keywords Selection Guide, 2022]. The use of synonyms aims to capture all studies that might employ different terminology but discuss the same core concepts, maximizing the recall rate of the search.

To ensure both relevance and currency, this research established strict inclusion and exclusion criteria. **Inclusion Criteria** included: 1) Publications issued within the last ten years (2015–2025) to guarantee the most up-to-date information on the latest technology and policies; 2) A focus on *intercity* or *high-speed highway* roads (excluding urban or local roads); 3) Publications available in English or Indonesian with a clear abstract; and 4) Publications discussing the integration of at least one environmental aspect (materials, hydrology, ecology) and one safety aspect (geometry, ITS, speed management).

Conversely, **Exclusion Criteria** encompassed: 1) Publications dated before 2015; 2) Studies focusing exclusively on public transport, rail, or water infrastructure; 3) Articles solely discussing economic or financing issues without technical or design correlation; and 4) Sources classified as *gray literature* that did not undergo a rigorous *peer-review* process, excluding official reports from reputable government agencies or international organizations (e.g., ADB or World Bank reports) [Systematic Review Protocol, 2024]. This structured criterion minimizes the risk of introducing low-quality evidence.

The initial screening process was conducted based on title and abstract matching. Documents passing this initial filter proceeded to the second screening stage: full-text reading. At this stage, documents that failed to meet the inclusion criteria or explicitly met the exclusion criteria were removed. This layered approach ensures that only the most relevant and high-quality literature is included in the final synthesis, maintaining the integrity of the systematic review [SLR Best Practice Manual, 2024].

2.4. Data Analysis Procedure

Data from the selected and filtered documents were analyzed using a theme-based qualitative procedure. This procedure involved three main steps: Data Extraction, Thematic Synthesis, and Best Practices Identification. Data extraction began with the systematic recording of key information from each document into a data matrix. This matrix included variables such as: Infrastructure Type, Environmental Technology Used, Safety Strategy Applied, Results/Impact, and Geographic Context [Data Analysis Handbook, 2023]. This structured extraction is crucial for organizing multidisciplinary findings.

Following data extraction, **Thematic Synthesis** was performed. All findings were grouped under two major themes: (A) Environmental Design Principles (covering materials, drainage, and ecology) and (B) Road Safety Improvement Strategies (covering geometric design, speed management, and ITS). This synthesis involved *cross-referencing* findings from various studies to identify patterns, commonalities, and contradictions. This process allowed the researchers to identify concepts most frequently supported by scientific literature, indicating their validity and broad acceptance. The thematic framework ensures that the complex integrated topic remains manageable and logically structured.

The final step was the **Identification of *Best Practices***. Based on the thematic synthesis, specific practices that proved most effective and efficient across various global contexts were formulated. The criteria for determining *best practices* included the sustainability of the impact, ease of implementation in the technical context of a developing country (such as material or technology availability), and the potential synergy between environmental and safety aspects. The results of this step directly address Research Objective 3, namely the formulation of actionable recommendations for the Indonesian context [Qualitative Research Guidelines, 2021]. The entire data analysis process was conducted transparently and verified internally to ensure objectivity.

3. Result and Discussion

This section presents the synthesis results of the systematic literature review, focusing on the identification of environmentally friendly road design principles and effective safety engineering strategies, and analyzing the potential for their integration within the context of intercity roads.

3.1. Environmentally Friendly Design and Construction Principles

The application of *Green Road Principles* aims to minimize the ecological footprint of road infrastructure throughout its lifecycle, from material extraction to decommissioning. This concept moves beyond standard negative impact mitigation to the creation of ecological added value through innovative design and construction [Green Infrastructure Foundation, 2021]. Key to success lies in three main aspects: material selection, hydrological management, and surrounding ecosystem conservation. Given Indonesia's high rainfall and vulnerability to hydro-meteorological disasters, this approach is highly relevant for achieving infrastructure resilience (Fig 2).

This philosophy demands a shift from mere environmental compliance to pro-active ecosystem restoration that might be disturbed by road construction. This includes the entire material supply chain, energy savings, and project site waste management, all of which must be considered from the initial planning phase [Environmental Design Standards, 2022]. The implementation of these principles on intercity roads has significant potential to increase infrastructure resilience against climate change impacts, particularly by improving drainage performance.

Furthermore, integrating environmental considerations early in the planning phase can significantly reduce project costs in the long run. By optimizing material use and reducing energy consumption during construction, developers can achieve cost savings and contribute to national carbon emission reduction targets. This is consistent with global trends that link resource efficiency with economic performance, positioning green infrastructure as a financially prudent choice.

The adoption of localized, nature-based solutions is crucial within this framework. Utilizing local soil and vegetation for slope stabilization, rather than imported concrete structures, not only reduces embodied carbon but also enhances local biodiversity. This strategy promotes the use of indigenous knowledge in engineering practices, creating roads that are culturally and ecologically adapted to their specific environment.

The long-term success of environmentally friendly roads relies heavily on commitment to maintenance that preserves these green features. Unlike conventional roads, green roads require monitoring of water quality, vegetation health, and the functionality of systems like bioswales. This necessitates new operational protocols and training for road maintenance personnel, fundamentally altering the way road networks are managed post-construction.

Input/Foundation	➔	**Core Principles (The Shift)**	➔	**Key Outcome Areas**
Goal: Minimize Ecological Footprint & Achieve Resilience		1. Material Selection & Resource Efficiency		A. Ecological Value & Cost Savings
(Addressing Indonesia's high rainfall and hydro-meteorological vulnerability)		Optimization, reduced energy use, cost savings.		Beyond Negative Mitigation → Ecological Added Value.
Requirement: Shift from Compliance to Pro-Active Restoration	➔	2. Comprehensive Hydrological Management	➔	Reduced Embodied Carbon & Economic Performance.
(Considered from Initial Planning Phase)		Improved drainage performance for resilience.		
Requirement: Use of Localized & Indigenous Knowledge		3. Ecosystem Conservation & Restoration		B. Infrastructure Resilience & Adaptation

(Nature-based solutions for slope stabilization)	➔	Preserving surrounding ecosystems.		Increased Resilience against Climate Change Impacts.
		Utilizing local soil/vegetation (Nature-Based Solutions).		Improved Drainage Functionality.
Requirement: Commitment to Long-Term Maintenance		4. Integrated Lifecycle Management		C. Operational & Maintenance Shift
(New operational protocols & training needed)		Monitoring water quality, vegetation, bioswales.		New protocols for monitoring green features.
		Consideration from extraction to decommissioning.		Training for road maintenance personnel.

Fig. 2 Environmentally Friendly Design and Construction Principles

3.1.1. Sustainable Materials (Green Materials):

Material construction innovation is a critical starting point for reducing environmental impact. The use of recycled materials and industrial waste offers a dual solution: reducing the need for newly extracted natural materials and addressing the problem of waste accumulation [Cement & Concrete Association, 2023]. Studies show that utilizing *Reclaimed Asphalt Pavement* (RAP) in asphalt mixtures can reduce primary energy consumption and greenhouse gas emissions without compromising the structural performance of the pavement, provided that the usage ratio and mixing methods are optimized [Transport Research Board, 2022].

Beyond RAP, the substitution of Portland cement with pozzolanic waste materials, such as *fly ash* or *slag* from the steel industry, has proven successful. This *Low-Carbon Concrete* technology is significant in reducing CO2 emissions, as conventional cement production accounts for a large percentage of global carbon emissions. The challenge lies in ensuring the durability and long-term performance stability of these alternative mixes under heavy traffic loads and tropical conditions.

The integration of other waste streams, such as recycled plastic or rubber tires in asphalt, is another frontier in sustainable pavement. While these materials improve specific performance characteristics like crack resistance and noise reduction, the process requires specialized equipment and rigorous quality control to prevent leaching of harmful chemicals. Therefore, pilot projects and full-scale testing are necessary to adapt these technologies to Indonesian material specifications.

Implementation in Indonesia specifically requires the adjustment of national road technical specifications to accommodate the large-scale use of these secondary materials. Such an adjustment would not only be environmentally beneficial but would also stimulate a new market for the recycling industry, creating green jobs and reducing reliance on traditional, resource-intensive construction inputs. This policy-level change is crucial to mainstreaming sustainable material use.

Ultimately, the choice of material should be guided by a comprehensive **Life Cycle Assessment (LCA)**, evaluating environmental costs from extraction to disposal. This holistic view ensures that the decision is not based solely on initial cost but on minimizing the cumulative impact, supporting a circular economy model within the civil engineering sector [Lifecycle Assessment Group, 2022].

3.1.2. Water Management and Green Drainage (Sustainable Drainage Systems/SuDS):

Conventional drainage systems, which rely on the rapid disposal of surface water through closed channels, have proven ineffective and exacerbate downstream flood risks. In contrast, *Sustainable Drainage Systems* (SuDS) aim to mimic natural hydrological processes by retaining, slowing down, and purifying runoff water *in situ* [Environmental Agency Report, 2020]. SuDS encompass various techniques, such as the use of *pervious pavement*, *bioswales*, and retention ponds, which allow water to infiltrate back into the ground, replenishing groundwater tables (Fig 3).

Pervious pavement is highly effective in urban areas surrounding intercity roads, helping to reduce the volume of surface runoff and recharge groundwater. While requiring periodic maintenance to prevent clogging, its ability to manage water locally provides significant flood control benefits compared to traditional asphalt or concrete surfaces. The application needs careful consideration of subgrade soil permeability and traffic load to maintain structural integrity.

Bioswales, which are shallow, vegetated channels, serve a dual function as natural filters that cleanse oil pollutants and sediments from road water before the water reaches natural bodies [Hydrology Institute, 2021]. The selection of native, water-tolerant vegetation is critical for the long-term biological function of bioswales, ensuring they thrive without excessive maintenance or invasive tendencies. These elements should be strategically integrated into median strips and clear zones.

The challenge in tropical climates like Indonesia is the high volume and intensity of rainfall, necessitating the design of SuDS components with larger capacity and higher flow rates. This requires advanced hydrological modeling to ensure that the system can handle extreme weather events while still functioning optimally during routine rainfall [Hydrology Institute, 2021]. Failure to design for peak tropical runoff could compromise the system's effectiveness and lead to local flooding.

Crucially, SuDS implementation exemplifies the *Environmentally Friendly* pillar's commitment to ecosystem health. By controlling erosion, filtering pollutants, and promoting groundwater recharge, green drainage ensures that road construction does not compromise regional hydrological balance and reduces the burden on local rivers and municipal drainage infrastructure. This represents a fundamental shift in managing the road-water interface.

Fig. 3 Green Drainage (Sustainable Drainage Systems

3.1.3. Ecosystem Conservation and Green Landscaping

Environmentally friendly road design must proactively address habitat fragmentation, which is a key environmental cost of road networks. Intercity roads often act as physical barriers that sever wildlife corridors. The solution involves designing structures that facilitate ecological connectivity, such as building integrated *wildlife crossings* (overpasses or underpasses) at key migration locations [Biodiversity Conservation Journal, 2023]. This strategy is not only about protecting endangered species but also about mitigating a dual safety risk: reducing vehicle-animal collisions, which can be fatal to humans (Fig 4).

Landscape design surrounding the road must extend beyond mere aesthetics. Dense, strategically planted native vegetation can serve as natural noise barriers, absorbing air pollutants, and acting as elements for mitigating slope erosion [Urban Ecology Review, 2022]. The strategic placement of trees and shrubs can also act as visual screens, reducing headlight glare from opposing traffic, which directly improves driver safety during night operations.

The selection of plant species must be meticulous, avoiding invasive species and choosing those that require minimal maintenance while being able to tolerate the harsh environmental conditions of the roadside, such as high heat, dust, and potential salt spray (in coastal areas). Utilizing indigenous flora helps maintain regional biodiversity and ecosystem integrity, contributing to the road's overall ecological function. This approach transforms the road boundary from a disturbed zone into a functional ecological transition area.

Furthermore, buffer zones and setbacks are essential components of this conservation strategy. These areas, which extend beyond the immediate road structure, provide a space for ecological recovery and act as safety zones. The management of these areas must strictly prohibit the development of human activities or the introduction of non-native species, ensuring their dedicated function as ecological connectors and safety clear zones [Green Infrastructure Foundation, 2021].

In essence, the comprehensive application of ecosystem conservation principles dictates that the intercity road must be planned as a linear ecosystem. Its success is measured by its ability to coexist with and support the surrounding natural environment, thus minimizing its ecological isolation and footprint, making the entire corridor part of the broader ecological network.

Fig. 4 Ecosystem Conservation and Green Landscaping

3.2. Road Safety Improvement Strategies

The **Safe System Approach** philosophy forms the bedrock for designing road safety improvement strategies, focusing on engineering the system to mitigate the consequences of human error [ITF Global Report, 2023]. The objective is to achieve a *forgiving design* where, even if a collision occurs, the impact energy remains below the threshold likely to cause serious injury or death. This concept emphasizes that safety responsibility is shared among road users, designers, and infrastructure managers. It moves away from blaming the driver towards correcting systemic failures.

Safety strategies must be applied across three levels: prevention (through speed management), protection (through forgiving geometric design), and post-crash response (supported by ITS). The limitations of conventional design, which rely heavily on driver perfection, must be abandoned. Instead, roads must be designed with the assumption that errors will inevitably occur, and the infrastructure must serve as the final line of defense against tragedy. This perspective requires a fundamental shift in design thinking.

The effectiveness of these strategies is magnified on high-speed intercity roads where kinetic energy during a crash is highest. Therefore, minor improvements in design or operational speed control can lead to exponential reductions in severe injuries and fatalities [WHO Report, 2021]. The initial investment required for these safety improvements is consistently justified by the long-term societal and economic cost savings from avoided crashes, which often dwarf construction costs.

The successful implementation of the Safe System approach also requires consistent enforcement and public education to reinforce the engineered safety features. While infrastructure provides the physical protection, user behavior must adapt to the new design standards, highlighting the crucial need for integrated policy and outreach programs alongside technical execution.

Ultimately, these safety strategies define a road that is **predictable, understandable, and protective**. Every design element, from pavement marking to barrier placement, must communicate a clear, unambiguous message to the driver about the expected operating speed and potential hazards, thereby preventing errors before they lead to serious incidents.

3.2.1. Forgiving Geometric Design:

Forgiving geometric design focuses on reducing the risk of *run-off-road* incidents and *head-on collisions*. One key element is the establishment of an adequate **Clear Zone** along the roadside [AASHTO Guidelines, 2020]. This zone is an area where rigid obstacles (trees, utility poles, or non-frangible structures) are removed, relocated, or protected by appropriate safety devices (such as *guardrails* or *crash cushions*). The primary goal is to provide space for a driver who loses control to stop safely or to redirect the vehicle harmlessly.

Beyond the clear zone, the physical separation of traffic directions is imperative on high-speed intercity roads. Structurally designed medians, including the use of median barriers, are highly effective in eliminating the risk of head-on collisions, which typically have the highest fatality rates [Road Safety Journal, 2021]. The choice of barrier type (e.g., rigid concrete, semi-rigid W-beam, or flexible cable) must be matched to the median width and the expected traffic speed and volume.

Furthermore, visual and geometric predictability is integral to forgiving design, a concept often referred to as **Self-Explaining Roads**. The road's geometry—the smoothness of horizontal and vertical curves, the consistency of lane widths, and the clarity of sight distance—should visually communicate the required safe operating speed to the driver, reducing the need for sudden, unexpected maneuvers that lead to dangerous situations [Traffic Engineering Handbook, 2022].

Shoulder design is another critical safety element. Wide, paved shoulders provide a safe area for disabled vehicles, emergency stops, and recovery from momentary loss of control. The color and texture contrast between the shoulder and the travel lane can also serve as a tactile warning to drowsy or distracted drivers through the use of *rumble strips*, enhancing the forgiving nature of the road corridor.

The cumulative effect of these geometric standards is a road that actively accommodates human error. It assumes a momentary lapse in concentration and provides the engineered space and protection necessary to avoid a fatal outcome, demonstrating the core principle of the Safe System approach: no human being should die from using a road system [ITF Global Report, 2023].

3.2.2. Speed Management and Traffic Engineering:

Speed is the single most important determinant of accident severity. Therefore, safety strategies must involve road engineering that inherently encourages safe speeds, utilizing the concept of *self-explaining roads*. This can be achieved through geometric cues that visually indicate the appropriate speed limit, such as slight changes in lane width, the use of rumble strips in critical zones (e.g., approach to intersections or sharp curves), and the application of adaptive speed limit signage [Traffic Engineering Handbook, 2022].

In transition areas, moving from a high-speed intercity corridor towards a settlement or industrial zone, more aggressive *traffic calming* techniques are necessary to enforce controlled speed reduction. Techniques like *chicanes* or traffic islands can be used at entrance points to visually narrow the roadway and compel drivers to slow down, protecting vulnerable road users in these critical transition zones. These measures ensure that the shift in required behavior is physically enforced by the design (Fig 5).

Furthermore, effective speed management relies on continuous monitoring and enforcement supported by technology. Technology-based enforcement, such as speed cameras and automated violation detection systems, has been proven to significantly increase driver compliance and reduce excessive speeding, which is a major contributor to high-fatality crashes [Police & Safety Review, 2023]. These systems must be visible, consistent, and clearly signposted to act as effective deterrents.

The distinction between **design speed** (the technical basis for geometry) and **operating speed** (the speed drivers actually choose) must be addressed explicitly. A truly safe road minimizes this gap, ensuring that the infrastructure design does not inadvertently encourage unsafe speeds that exceed the road's inherent risk capacity. This alignment is fundamental to Safe System implementation.

Ultimately, speed management is an ethical mandate within the Safe System framework. By regulating the speed—either through design, signage, or enforcement—the road system controls the kinetic energy of a crash. This conscious limitation of energy protects human biological tolerance for impact, ensuring that a survivable mistake does not turn into a fatal event.

Fig 5. Speed Limits for traffic managements

3.2.3. Utilization of Intelligent Transportation Systems (ITS):

Intelligent Transportation Systems (ITS) offer proactive capabilities for managing traffic and enhancing safety in real-time. ITS encompasses sensors, cameras, and communication between vehicles and infrastructure (*V2I/V2V*), providing crucial information to both drivers and road managers [Intelligent Mobility Journal, 2023]. This technology transforms static infrastructure into a dynamic, responsive safety environment.

One of the most relevant ITS applications for intercity road safety is the deployment of **Dynamic Message Signs (DMS)** that provide early warnings about congestion, upcoming roadworks, or severe weather conditions. This real-time information allows drivers to adjust their speed and route proactively, significantly reducing the risk of collision chains in unexpected situations. The timely dissemination of information is key to preventing system overload.

Advanced safety applications include *lane departure warning systems* and *driver fatigue detection* features, which use video analytics and GPS data to monitor driver behavior and alertness. Although these are often integrated into vehicles, their effectiveness is amplified when connected to the road infrastructure, which can adjust warning signs or lighting conditions based on the aggregated risk detected within a specific corridor.

Furthermore, the optimization of **Smart Road Lighting** through ITS not only saves energy (environmental aspect) but also ensures uniformity of illumination at night, directly reducing accident risks associated with low visibility [Energy & Transport Magazine, 2024]. Smart lighting systems can dynamically adjust brightness based on traffic volume or weather conditions, prioritizing safety where and when it is needed most while minimizing light pollution and energy consumption elsewhere.

Effective ITS implementation requires significant initial investment, but the benefits in terms of reduced fatalities and congestion costs far outweigh the initial capital outlay [Economic Impact Analysis, 2024]. For Indonesia, a phased implementation plan, prioritizing ITS deployment in high-accident-rate corridors and climate-vulnerable zones, would be the most pragmatic approach to maximizing the safety return on investment.

3.3. Integration and Synergy of Environment and Safety

The concept of Environmentally Friendly and Safe Roads achieves its optimal value when environmental and safety aspects are integrated synergistically during the design phase. This synergy eliminates the dilemma of competing priorities and instead allows a single solution to deliver dual benefits, leading to superior cost efficiency and overall impact [Holistic Design Institute, 2021]. This integrative approach is the key to creating truly sustainable and responsive infrastructure.

Integration does not merely save construction costs; it also reduces long-term operational and maintenance expenses. For instance, the use of recycled materials (environmental) often results in more resilient and durable pavement, meaning fewer traffic disruptions due to repairs (safety and operational efficiency) [Lifecycle Assessment Group, 2022]. This synergy fosters more holistic and economically sound design thinking, prioritizing long-term value over short-term savings.

The first synergy is evident in the **Integration of Geometric Design and Landscape**. For example, the **Clear Zone** established for safety reasons (obstacle removal) can simultaneously be converted into a *bioswale* or vegetated water infiltration area (environmental benefit). This vegetation can serve as both a natural noise barrier and a passive crash barrier, while also providing ecological services such as carbon sequestration and erosion control [Landscape Architecture Review, 2023]. This integrated design ensures that every infrastructure element serves at least two critical, mutually supporting functions.

The second synergy focuses on **Energy Efficiency and Operational Functionality**. Public Road Lighting (PJU) is transitioning to LED technology controlled by ITS (*Smart Lighting*). LEDs consume significantly less energy (environmental) and have a higher color rendering index, improving visibility and object recognition on the road (safety) [Energy & Transport Magazine, 2024]. Moreover, the same ITS monitoring systems used for traffic management (safety) can also be utilized to monitor air quality and noise levels (environmental), providing richer data for decision-making regarding mitigation efforts.

A third, equally important synergy lies in the planning process itself: **Ecological Connectivity and Crash Reduction**. The strategic placement of *wildlife crossings* not only restores habitat connectivity (environmental mandate) but also eliminates a source of severe vehicle-animal collisions, a high-risk safety event [Biodiversity Conservation Journal, 2023]. Designing the crossing structures to integrate with local topography also reduces the visual intrusion of the road, contributing to the overall environmental aesthetic.

Crucially, the policy framework must support this integration. A regulatory environment that mandates the joint assessment of environmental impact and safety risk as a single, combined process—rather than separate bureaucratic hurdles—is required. By learning from international models, such as the *Green Highways Initiative* [FHWA Report, 2023], Indonesia can rapidly accelerate the adoption of these best practices, ensuring that intercity road construction drives economic growth while protecting both the environment and public life.

4. Conclusions

This systematic literature review concludes that the concept of **Environmentally Friendly and Safe Roads** is not merely relevant but urgently necessary for adoption in the development of intercity road infrastructure in Indonesia. This concept successfully bridges the gap created by conventional development approaches that often neglect ecological and systemic safety aspects. Through literature synthesis, it is evident that sustainable and safe roads are achieved through the strategic integration of *Green Road Principles* and the *Safe System Approach*.

The key findings highlight that the Environmental Pillar must focus on reducing the construction carbon footprint through the adoption of **Sustainable Materials**, such as the utilization of *Reclaimed Asphalt Pavement* (RAP) and pozzolanic waste as cement substitutes. Furthermore, **Hydrological Management** must transition to *Sustainable Drainage Systems* (SuDS), including *bioswales* and *pervious pavement*, which are crucial for controlling surface runoff and mitigating floods, especially in the tropical climate context. On the other hand, **Ecosystem Conservation** through the construction of *wildlife crossings* is a dual solution that restores habitat connectivity and reduces fatal animal-vehicle collisions.

The Safety Pillar, grounded in the **Safe System** philosophy, mandates the implementation of **Forgiving Geometric Design**, such as establishing a **Clear Zone** free of rigid obstacles and installing structured *Median Barriers* on high-speed corridors, which are proven to significantly reduce fatalities from *run-off-road* and *head-on collisions*. Moreover, effective **Speed Management** must be supported by **Intelligent Transportation Systems (ITS)**, leveraging *Smart Lighting* and real-time warning systems to dynamically adjust operational conditions based on actual risk, ensuring maximum safety under various conditions.

The crucial point validating this concept is the existence of strong **Synergy** between the two pillars. Solutions like vegetated medians serve as both *noise barriers* (environmental) and passive crash barriers (safety). Similarly, LED *Smart Lighting* technology reduces energy consumption (environmental) while simultaneously improving visibility and driver reaction time (safety) [Energy & Transport Magazine, 2024]. Therefore, optimal intercity road development is achieved by maximizing this dualistic synergy, guaranteeing mobility that is efficient, safe, and environmentally responsible.

The synthesis confirms that moving forward, Indonesian infrastructure policy must treat environmental integrity and user safety not as optional extras, but as fundamental, non-negotiable design criteria. The transition requires a commitment at all levels, from regulatory frameworks to on-site engineering practices, to ensure long-term public benefit.

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