

Assessment of Environmental Impacts for Highways Using Sustainable Development Indicators: Review

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Abstract: Building and maintaining highways can have major effects on the environment, society, and economy. To reduce these impacts and encourage sustainability, it's important to evaluate highways using a set of sustainable development indicators (SDIs). This review looks at different SDIs used worldwide to assess how highways affect the environment, focusing on areas like air pollution, noise, biodiversity, land use, and resource consumption. It discusses methods for using these indicators in environmental assessments and outlines the challenges of making highways more sustainable. The review also explores new trends in applying SDIs and stresses the need to balance environmental concerns with economic and social growth. Finally, it offers suggestions for better incorporating SDIs in highway planning to support long-term sustainability.

Keywords: Sustainable development, Environmental impact, Sustainability, Environmental management, Infrastructure.

I. INTRODUCTION

Highways are essential for modern transportation, enabling efficient movement of goods and people, connecting cities, and promoting economic development. However, these benefits often come at a significant environmental cost (Hashemi et al., 2021). The construction and operation of highways can lead to land degradation, air and water pollution, loss of biodiversity, and increased carbon emissions. As global awareness of environmental sustainability grows, there is a pressing need to evaluate the impact of highways in a more structured and measurable way (Babashamsi et al., 2016). Traditional environmental assessments of highways have focused primarily on short-term impacts, such as air pollution or noise during construction. While these assessments are important, they often overlook the broader, long-term effects on ecosystems, local communities, and climate change (Hashemi et al., 2021). This has created a gap in how the sustainability of highway projects is measured and managed. To address this, researchers and

policymakers are increasingly turning to Sustainable Development Indicators (SDIs) as a more holistic way to assess the environmental, social, and economic impacts of highways (Ledoux et al., 2005).

SDIs offer a structured framework for evaluating a range of sustainability factors, from environmental protection to social equity and economic viability. These indicators can help assess the broader impact of highways on air quality, resource use, land use changes, and even the social well-being of nearby communities. By integrating SDIs into highway project assessments, decision-makers can take a more balanced approach, weighing both the benefits and costs of infrastructure development (Boulanger, 2008). One of the major environmental concerns related to highways is air pollution. Vehicle emissions from highways contribute to global warming and pose health risks to humans and wildlife (Tasaki et al., 2010). Sustainable development indicators related to air quality focus on monitoring pollutants such as carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter (PM). These indicators help in identifying the levels of pollution caused by highway traffic and in promoting cleaner alternatives like electric vehicles or stricter emission regulations (Garnåsjordet et al., 2012).

Noise pollution is another critical issue. Highways running through or near residential areas can have a significant impact on the quality of life for local residents (Boulanger, 2008). Prolonged exposure to traffic noise has been linked to health problems like sleep disturbances and cardiovascular issues. SDIs related to noise pollution can measure the extent of the impact and suggest mitigation strategies such as noise barriers or better urban planning to reduce noise exposure (Babashamsi et al., 2016).

Biodiversity loss is a less visible but equally important impact of highway development. The construction of highways often disrupts natural habitats, leading to the loss of plant and animal species (Matta et al., 2011). SDIs focusing on biodiversity aim to measure the effects of highway projects on ecosystems, track species at risk, and promote conservation measures that can protect wildlife while accommodating infrastructure needs

(Green et al., 2005). Land use and resource consumption are also important aspects of highway sustainability. Highway construction requires vast amounts of land and materials like concrete, steel, and asphalt. These resources have significant environmental footprints (Amekudzi et al., 2015). Sustainable development indicators related to resource consumption track the efficiency and sustainability of materials used in highway projects. They also assess how highway development affects land use patterns, potentially encouraging urban sprawl or deforestation (Li et al., 2022).

Water pollution and management are other areas where highways can have a detrimental impact. Runoff from highways can carry pollutants like oil, chemicals, and heavy metals into nearby water bodies, degrading water quality and affecting aquatic ecosystems (Hoang et al., 2019). SDIs can be used to monitor water pollution levels and suggest measures such as better drainage systems and pollution control technologies to mitigate these effects (He et al., 2022). Social impacts are equally important when considering highway sustainability. Highways can both positively and negatively affect nearby communities. While they provide economic opportunities and easier access to services, they can also lead to displacement, social isolation, or increased accidents (Babashamsi et al., 2016). Sustainable development indicators related to social well-being focus on how highway projects affect local populations, emphasizing the need for equitable access, community engagement, and minimizing adverse effects on people's lives (Boulanger, 2008). In addition to environmental and social concerns, economic factors must also be considered. Highways are vital for economic growth, but the benefits should not come at an unsustainable cost. SDIs can assess the economic viability of highway projects by analyzing factors such as long-term maintenance costs, the economic uplift provided to surrounding areas, and the trade-offs between economic growth and environmental degradation (Hashemi et al., 2021).

The growing focus on sustainability in highway projects reflects a broader trend in global infrastructure development. Governments and organizations worldwide are adopting policies that emphasize the need for greener, more sustainable infrastructure (Ledoux et al., 2005). Incorporating SDIs into highway planning and assessment provides a practical and measurable way to align highway development with sustainable development goals, ensuring that economic growth is balanced with environmental protection and social equity (Ruggerio, 2021).

The use of SDIs in highway construction, planning, and management is becoming increasingly essential as the world grapples with the environmental, social, and economic consequences of infrastructure development. Highways, while critical for economic growth and connectivity, can cause long-lasting harm to ecosystems, natural resources, and communities if not properly managed (Thomé et al., 2016). SDIs provide a comprehensive framework to assess and mitigate these impacts, ensuring that highways are designed and operated in ways that support long-term sustainability goals. They serve as a guide for decision-makers to balance the benefits of infrastructure development with the need to protect the environment and maintain social well-being (Hanna & Comín, 2021).

One of the key reasons for the importance of SDIs is their ability to offer a holistic view of highway projects. Traditional assessments often focus narrowly on short-term impacts like cost or immediate environmental damage, while ignoring the broader and more complex long-term consequences (Fischer & Amekudzi, 2011). SDIs, by contrast, incorporate a wide range of factors, from air quality and biodiversity to social equity and resource consumption. This allows for a more comprehensive understanding of how a highway will affect its surroundings over time. As a result, SDIs help in identifying risks and opportunities that might otherwise be overlooked, leading to better, more informed planning and management (Fay et al., 2011).

Incorporating SDIs into highway planning is also crucial for minimizing environmental degradation. Highways can contribute significantly to air and water pollution, noise, and habitat destruction. Indicators related to pollution levels, carbon emissions, and ecosystem health can guide the adoption of cleaner technologies and greener construction practices (Thomé et al., 2016). For example, monitoring air quality indicators can push for the use of electric vehicles or more efficient traffic management systems, reducing the carbon footprint of highway operations. By actively tracking and responding to these indicators, planners can take steps to reduce the environmental impact from the very beginning of a project (Fischer & Amekudzi, 2011). SDIs also play an important role in ensuring that highway projects are socially sustainable. Highways often cut through communities, leading to displacement, changes in land use, and altered access to services. Indicators that assess the social impacts of highways, such as those related to community engagement, public safety, and equitable access, ensure that the voices and needs of affected populations are considered. This can help to avoid social conflicts and ensure that the benefits of a highway, such as improved transportation and economic opportunities, are shared fairly across different groups (Fay et al., 2011).

Finally, SDIs are essential for ensuring the long-term economic viability of highway projects. Highways represent massive investments, and their success depends on how well they are maintained and how they adapt to future challenges, such as climate change or changing traffic patterns (Thomé et al., 2016). Economic indicators can help assess the efficiency of resource use, long-term maintenance costs, and the overall return on investment. By incorporating these into the planning and management process, highway projects can be designed to deliver maximum value while avoiding costly environmental or social problems down the road (Hanna & Comín, 2021). In this way, SDIs ensure that highway infrastructure supports sustainable development in every sense—environmental, social, and economic.

II. SUSTAINABLE DEVELOPMENT AND INFRASTRUCTURES

Sustainable development refers to a way of progressing as a society that meets the needs of the present without compromising the ability of future generations to meet their own needs. It's a balance between economic growth, environmental protection, and social well-being. This concept emerged in response to growing concerns about the long-term impacts of unchecked industrialization, resource depletion, and environmental

degradation. Sustainable development seeks to harmonize human activity with the natural world, ensuring that progress today doesn't come at the cost of the planet or future human well-being (Adepoju, 2021). The concept gained widespread recognition with the 1987 Brundtland Report by the World Commission on Environment and Development, which defined sustainable development as development that is both economically viable and environmentally sound (Bacior & Prus, 2018). It recognizes that our planet's resources are finite, and if we continue to consume them at the current rate without regard for their renewability or the environmental damage we cause, we will face serious consequences in the future (Hanna & Comín, 2021). Therefore, sustainable development calls for a shift from short-term gains to long-term planning (Ruggerio, 2021).

A main aspect of sustainable development is environmental sustainability (Ledoux et al., 2005). This involves protecting ecosystems, managing natural resources responsibly, and reducing pollution. It encourages practices that preserve biodiversity and mitigate climate change, such as transitioning to renewable energy, reducing waste, and promoting sustainable agriculture (Bacior & Prus, 2018). Environmental sustainability isn't just about conserving resources; it's about creating systems where human activities can coexist with nature, maintaining ecological balance so that future generations can enjoy clean air, water, and fertile land (Thacker et al., 2019).

Another pillar of sustainable development is social sustainability, which focuses on improving human well-being and ensuring equal access to resources, services, and opportunities. This aspect emphasizes reducing poverty, promoting social justice, and ensuring that everyone, regardless of background, has the opportunity to live healthy, productive lives (Thacker et al., 2019). Social sustainability also includes ensuring that development projects, such as infrastructure or urban expansion, do not displace communities or marginalize vulnerable populations. It highlights the importance of inclusivity and equity in development processes (Wang et al., 2018). Economic sustainability is the third critical component of sustainable development (Ruggerio, 2021). It advocates for economic systems that support long-term growth without exhausting natural resources or causing significant environmental harm. This requires a shift towards economies that rely on renewable resources, green technologies, and efficient production processes (Thacker et al., 2019). Economic sustainability also means creating jobs and wealth in a way that supports both individual livelihoods and the broader society while ensuring that the benefits of economic growth are distributed fairly.

Ultimately, sustainable development is about creating a balance between these three pillars such as environmental, social, and economic, so that development can proceed in a way that benefits everyone, both now and in the future. It requires a fundamental rethinking of how we use resources, how we structure our economies, and how we interact with the planet. The pursuit of sustainable development is not just a goal for governments or businesses, but a shared responsibility for individuals, communities, and organizations to ensure that progress is sustainable, equitable, and inclusive for all (Bacior & Prus, 2018).

Sustainable development plays a crucial role in shaping the impact of highway construction and infrastructure development.

Highways are essential for transportation and economic growth, but their construction can lead to significant environmental, social, and economic challenges (Žák, 2019). By integrating sustainable development principles into the planning, design, and management of highways, it is possible to reduce negative impacts while promoting long-term benefits (Attahiru et al., 2019). This approach helps ensure that highway projects support environmental protection, social well-being, and economic viability (Li et al., 2014). One of the most significant impacts of sustainable development in highway construction is the reduction of environmental harm (Ruggerio, 2021). Traditional highway projects can contribute to air and water pollution, habitat destruction, and increased carbon emissions. Sustainable development encourages the use of eco-friendly materials, renewable energy sources, and advanced construction techniques that minimize these impacts (Attahiru et al., 2019). For example, incorporating green infrastructure such as permeable pavements, bioswales, and natural drainage systems can reduce stormwater runoff and improve water quality (Bacior & Prus, 2018). Additionally, sustainable practices like reducing construction waste and limiting deforestation can preserve ecosystems and biodiversity (Ruggerio, 2021).

Sustainable development also promotes the idea of designing highways in ways that enhance social equity and community well-being. Highways often cut through communities, potentially displacing residents, creating noise pollution, and reducing access to essential services (Bacior & Prus, 2018). By prioritizing community engagement and considering the social impacts of highway construction, sustainable development can help avoid these negative outcomes (Hanna & Comín, 2021). Projects can be designed to minimize community disruption, improve public transportation options, and provide safe pedestrian pathways. This ensures that highways not only serve transportation needs but also enhance the quality of life for local populations (Žák, 2019). Another major benefit of integrating sustainable development into highway infrastructure is the economic advantage of creating long-lasting, resilient projects. Sustainable highways are designed to withstand future environmental challenges, such as extreme weather events and climate change, which reduces long-term maintenance costs. In addition, adopting energy-efficient technologies, such as smart traffic management systems and renewable energy-powered streetlights, can lower operational expenses and reduce energy consumption. Sustainable development also supports the creation of green jobs, stimulating local economies through investments in renewable energy, construction innovation, and environmental conservation (Thacker et al., 2019).

From a resource management perspective, sustainable development encourages the responsible use of materials and energy in highway construction. Highways require large amounts of raw materials like concrete, steel, and asphalt, which can have significant environmental footprints if not sourced sustainably. Sustainable construction practices prioritize the use of recycled materials and energy-efficient production methods, reducing the overall environmental impact of resource extraction and processing. Additionally, the incorporation of renewable energy sources, such as solar panels or wind turbines along highways, can contribute to a reduction in greenhouse gas emissions and promote energy sustainability (Žák, 2019). By adopting

sustainable practices, highway systems can be designed and managed in ways that protect the environment, promote social equity, and ensure long-term economic resilience (Attahiru et al., 2019). Sustainable highways not only meet transportation needs but also contribute to a more sustainable future, where infrastructure development aligns with the principles of responsible resource use, community engagement, and ecological balance (Thacker et al., 2019).

III. BACKGROUND REVIEW

Liang-feng & Liu (2002), using the hierarchical decision-making approach and MCDM system, prioritized the most influential criteria and indicators of sustainable construction in green building and civil engineering projects. They emphasized that identifying appropriate criteria is crucial for achieving optimal decision-making. Following sustainable construction guidelines, they noted, provides optimal models applicable to all projects. Zai-qiu (2008) developed a rapid prediction model for developmental and environmental risks in civil engineering projects, especially railway projects, using fuzzy computational logic. This researcher identified the features and criteria involved in railway project development, prioritized each criterion, and evaluated their impact on execution risks in these projects.

Ravanshadnia et al. (2010) employing a hybrid AHP, fuzzy logic, and MCDM systems, assessed engineering and environmental criteria in construction contract projects. They identified and defined hierarchical criteria and sub-criteria, applied parametric weighting using AHP, and employed fuzzy coefficients to assess the impact of these criteria. These coefficients were used for multi-criteria prioritization in civil engineering projects, categorizing the main and effective indicators for the projects. Pineda (2012), in a study argued that environmental degradation would reduce the HDI by 8% by 2050, and in a pessimistic scenario, the reduction could reach as much as 15%. Chou et al. (2013) used fuzzy logic, AHP analysis, and MCDM systems to offer strategies for managing civil engineering projects. These researchers presented a comprehensive model of key factors for sustainable development and optimal management in construction projects.

Nguyen et al. (2015) used a hybrid AHP model, combined with fuzzy logic and MCDM systems, to quantify and evaluate the complexities in railway transport projects. The researchers pointed out that identifying criteria, sub-criteria, and effective alternatives in developmental and infrastructure projects is significantly more complicated than in regular civil engineering projects, with many uncertainties involved. They highlighted that traditional approaches are inadequate for handling these uncertainties. By applying fuzzy logic, which defines a range of variability, they were able to address these uncertainties more effectively, and the model was implemented with a high degree of precision. Sarkar et al. (2018) utilized a comprehensive computational fuzzy logic model and AHP-MCDM decision-making system to identify and extract critical factors affecting railway projects in western India, with a focus on environmental and sustainable development indicators. They prioritized and categorized key parameters based on risk factors and their importance in infrastructure projects. The researchers emphasized that the inherent complexity and uncertainties

present in infrastructure projects are critical factors that must be addressed for optimal and sustainable project management.

Yin et al. (2019) reported on the successful implementation of a hybrid model combining AHP, fuzzy logic, and MCDM to identify and prioritize the key criteria in road and railway infrastructure projects in China. The study utilized green management indicators and guidelines to inform the decision-making process. By employing optimized decision-making matrices with suitable consistency (CR less than 10%), they were able to assign weights to the most important operational and environmental features and extract the interactive effects of these factors. Andrić et al. (2019a), focusing on the Belt and Road railway project in China, identified the critical path and risks associated with the railway project through sensitivity analysis and fuzzy logic based on sustainable development principles. They recognized the key criteria involved in generating risks and classified them by defining fuzzy membership functions. By assigning weights according to the importance and impact of each parameter, they prioritized the project's elements in order to better manage risks. In another study, Andric et al. (2019b) used fuzzy logic to develop a decision-making model for infrastructure projects, following environmental and sustainable development guidelines. This model was applied to the central Belt and Road railway project in China, allowing the researchers to identify and define the main criteria involved. They developed a decision operator to optimize their model, which was a combination of AHP, fuzzy logic, and MCDM, to categorize the key influencing factors. Abdel-Basset et al. (2020) conducted a study that considered the uncertainties of project conditions, their interaction with the environment, and the duration of project activities. They developed a fuzzy-based resource leveling model to minimize the cost fluctuations of daily resource use by scheduling activities according to precedence relationships throughout the project's timeline. To overcome the ambiguity caused by environmental challenges in executable plans, the researchers designed the resource leveling model based on a neutrosophic set. This model was utilized to estimate the activity duration, effectively addressing uncertainties and optimizing resource allocation.

IV. CONCLUSION

In conclusion, the integration of SDIs in highway construction, planning, and management is essential for minimizing environmental impacts and ensuring long-term economic and social benefits. By using MCDM systems and approaches like AHP and fuzzy logic, researchers have demonstrated the importance of identifying and prioritizing key environmental, social, and operational criteria in infrastructure projects. These methods allow for a more comprehensive understanding of the uncertainties and complexities involved in highway projects, leading to more informed decision-making and improved project outcomes. The studies reviewed emphasize the need for sustainable practices in large-scale infrastructure projects, particularly in transportation systems such as highways and railways. By leveraging green management strategies, optimized decision-making models, and resource leveling techniques, these projects can reduce environmental degradation,

manage risks more effectively, and achieve sustainable development goals. Overall, integrating SDIs into the planning and execution of highway projects not only improves environmental and social outcomes but also enhances the resilience and sustainability of infrastructure systems.

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AUTHORS' CONTRIBUTIONS

Mohammad Alami Parvin and Akbar Shokir Tazehkand conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and were responsible for drafting the initial manuscript. Murad Ramiz Ahmadoglu assisted in the development of the methodology and performed validation checks, provided supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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