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Highway Maintenance Schemes: Integrating Environmental Sustainability into Value Management

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Abstract*: Assessing the environmental sustainability of highway projects is crucial for setting goals, evaluating progress, guiding decision-making and demonstrating accountability to the public. Sustainability assessment can occur at multiple scales, from evaluating specific materials and construction practices to analyzing the cumulative impacts of entire highway networks. A variety of sustainability rating systems, metrics, and tools have been developed for measuring and scoring the environmental performance of transportation infrastructure. The importance of environmental sustainability in highway construction and maintenance cannot be overstated. Highways have a massive spatial footprint, with the U.S. Interstate Highway System alone covering nearly 47,000 miles as of 2020 (Federal Highway Administration, 2020). Globally, the length of paved roads exceeds 40 million kilometers and continues to rapidly expand (International Road Federation, 2022). The materials used in roads, such as aggregate, asphalt, concrete, and steel, are typically mined and manufactured through energy and emissions-intensive processes.*

Keywords: environmental sustainability of highway projects, setting goals, evaluating progress, guiding decision-making and demonstrating accountability

I. INTRODUCTION

Highway construction often involves extensive earthwork and land disturbance that fragments natural habitats, alters hydrology, and increases erosion and sedimentation. According to one estimate, roads and highways are responsible for 15-20% of habitat fragmentation in the U.S. (Barton et al., 2014). Impervious pavement also contributes to storm water runoff pollution, thermal pollution of waterways, and urban heat island effects. Additionally, vehicle emissions from traffic are a major source of air pollutants like particulate matter, nitrogen oxides, and volatile organic compounds, which have well-documented health impacts. From a climate change perspective, the transportation sector is one of the largest and fastest-growing sources of greenhouse gas emissions. In the U.S., transportation accounted for 27% of total emissions in 2020, with on-road vehicles making up over 80% of this share (Environmental Protection Agency, 2022a). Globally, on-road transport contributed 12% of total CO2 emissions from fuel combustion in 2019 (International Energy Agency, 2021). While efforts to improve vehicle efficiency and electrify fleets are underway, addressing the sustainability of highway infrastructure itself remains critical. Recognizing these multifaceted environmental challenges, transportation agencies at the federal, state, and local levels have increasingly embraced sustainability goals and initiatives in recent years. In the U.S., the Federal Highway Administration has outlined sustainability priorities around human health, environmental stewardship, climate change mitigation and resilience, equitable communities, and sustainable economic development (Federal Highway Administration, 2022). Many state DOTs have developed formal sustainability plans and use sustainability rating systems like Envision and Green roads for highway projects. However, assessing and achieving truly sustainable outcomes in the complex realm of highway construction and maintenance requires robust frameworks, consistent metrics, actionable strategies, and context-sensitive solutions. There is a need to critically examine current approaches, identify best practices and innovative techniques, and chart a course for continuous improvement in the sustainability performance of highways. This introductory chapter will provide an overview of key concepts, trends, challenges, and opportunities related to assessing environmental sustainability in highway construction and maintenance. Subsequent chapters will delve into specific sustainability indicators, tools, case studies, and recommendations for practitioners and policymakers.

II. RESEARCH METHODOLOGY

The research methodology is guided by the principles of systems thinking, life cycle assessment, and participatory action research. System thinking recognizes the interconnectedness and feedback among different components and stakeholders in highway projects, and seeks to understand their behavior and outcomes holistically (Checkland, 1999). Life cycle assessment (LCA) is a tool for quantifying the environmental impacts of products or processes from cradle to grave, considering all stages of raw material extraction, manufacturing, use, and end-of-life (ISO, 2006). Participatory action research involves collaborating with stakeholders to co-create knowledge, identify challenges, and develop solutions in an iterative and reflexive process (Whyte, 1991).

(i) Research Design- The research design for this study is a sequential mixed-methods approach that combines quantitative and qualitative data collection and analysis in a complementary and iterative manner (Creswell & Plano Clark, 2017). The rationale for using mixed methods is to provide a more comprehensive and nuanced understanding of the complex and multidimensional nature of sustainability in highway projects, and to triangulate and validate findings from different sources and perspectives (Greene et al., 1989). The research design consists of four main phases:

Phase 1 - Literature Review and Expert Consultation:

The first phase involves conducting a comprehensive review of the academic and grey literature on sustainability assessment in highway projects, and consulting with experts in the field to identify key issues, knowledge gaps, and best practices. The literature review follows a systematic and structured approach, using defined search terms, inclusion and exclusion criteria, and quality appraisal methods (Tranfield et al., 2003). The expert consultation involves semi-structured interviews with a purposive sample of researchers, practitioners, and policymakers in the highway sector, using a snowball sampling technique to identify additional participants (Patton, 2002).

The main outputs of Phase 1 are:

A synthesis of the state-of-the-art in sustainability assessment of highway projects, including definitions, frameworks, indicators, tools, and case studies.

A preliminary list of environmental aspects and impacts of highway projects, and their relative significance and priority based on literature and expert input.

A set of hypotheses and research questions to be tested and refined in subsequent phases.

Phase 2 - Life Cycle Assessment and Cost Analysis:

The second phase involves conducting detailed life cycle assessment (LCA) and life cycle cost analysis (LCCA) of selected highway construction and maintenance projects and alternatives. LCA is a quantitative tool for evaluating the environmental impacts of a product or process throughout its life cycle, from raw material extraction to end-of-life disposal or recycling (ISO, 2006). LCCA is a similar tool for evaluating the total cost of ownership of an asset, considering initial investment, operation, maintenance, and disposal costs (FHWA, 2002). The main data sources for the LCA and LCCA studies are:

Project documents and reports, such as plans, specifications, bid tabulations, and as-built drawings, obtained from highway agencies and contractors.

Environmental product declarations (EPDs) and life cycle inventory (LCI) databases, such as the US LCI Database (NREL, 2012) and the Ecoinvent database (Wernet et al., 2016), for material and process data.

Published literature and case studies on the environmental and economic performance of highway materials and technologies, such as recycled asphalt pavement (RAP), warm-mix asphalt (WMA), and permeable pavements.

Phase 3 - Survey and Case Studies:

The third phase involves conducting a survey and developing case studies to investigate the current practices, perceptions, and experiences of highway agencies, contractors, designers, and other stakeholders in implementing sustainable construction and maintenance practices. The survey is designed as a web-based questionnaire using Qualtrics software (Qualtrics, 2019), and distributed to a representative sample of highway professionals across different regions, organization types, and project roles. The survey questions cover topics such as:

Familiarity with and use of sustainability rating systems, guidelines, and tools for highway projects.

Perceived benefits, barriers, and enablers for adopting sustainable practices in highway projects.
Level of integration of sustainability considerations into project planning, design, construction, and maintenance processes.
Examples of successful and innovative sustainable highway projects and practices.
Phase 4 - Framework Development and Validation:
The fourth and final phase involves integrating the findings and insights from the previous phases to develop a comprehensive framework for assessing and improving the environmental sustainability of highway construction and maintenance projects. The framework is intended to provide a structured and systematic approach for incorporating sustainability considerations into the decision-making and management processes of highway projects, and for engaging stakeholders in the process.
The framework development follows an iterative and participatory approach, involving input and feedback from highway professionals, experts, and stakeholders through workshops, focus groups, and online collaboration tools. The framework is organized into several key components, such as:
Sustainability principles, goals, and objectives for highway projects
Sustainability indicators, metrics, and benchmarks for measuring and evaluating performance
Sustainability assessment tools and methods, such as LCA, LCCA, and rating systems
Sustainability strategies, technologies, and best practices for different project phases and contexts
Sustainability governance, communication, and reporting processes and templates
The framework is validated through pilot testing on selected highway projects and feedback from users and stakeholders. The pilot testing involves applying the framework to real-world projects and evaluating its usability, effectiveness, and impact on project outcomes and stakeholder satisfaction. The feedback is used to refine and improve the framework and develop implementation guidance and training materials.
The main outputs of Phase 4 are:
A validated and user-friendly framework for assessing and improving the environmental sustainability of highway construction and maintenance projects, including tools, templates, and guidance materials.
Case studies and lessons learned from pilot testing the framework on real-world projects, and recommendations for future implementation and scaling up.
A roadmap and action plan for disseminating and mainstreaming the framework in the highway sector, and for building capacity and leadership for sustainability among highway professionals and stakeholders.
(ii) Data Collection- The data collection for this study involves a combination of primary and secondary sources, and quantitative and qualitative methods, as described in the previous section. This section provides more details on the specific data collection procedures and instruments used in each phase of the research. using a systematic search and screening process, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2009). The main steps are:
Identification: Search relevant databases, such as Scopus, Web of Science, and Transport Research International Documentation (TRID), using defined keywords and phrases related to sustainability, highways, construction, maintenance, assessment, and indicators. Also search grey literature sources, such as government reports, conference proceedings, and industry publications.
Screening: Apply inclusion and exclusion criteria to the search results, based on factors such as relevance, language, publication date, and document type. Remove duplicates and irrelevant records.
Eligibility: Review the full text of the remaining records and assess their quality and suitability for the review, based on factors such as research design, data sources, methods, and conclusions.
Inclusion: Extract and synthesize the relevant data and insights from the eligible records, using a data extraction form and qualitative data analysis software, such as NVivo (QSR International, 2019).

III. RESULTS AND FINDINGS

The results and findings from the comprehensive study on the assessment of environmental sustainability in highway construction and maintenance. The data collected through literature review, expert interviews, life cycle assessments

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(LCA), life cycle cost analyses (LCCA), surveys, case studies, and stakeholder workshops have been rigorously analyzed to answer the four primary research questions:

What are the key environmental impacts and indicators of highway projects?

How do different highway construction and maintenance practices compare in terms of environmental impacts and costs?

What are the barriers, enablers, and best practices for implementing sustainable highway practices?

How can sustainability considerations be integrated into highway project decision-making?

The findings are organized thematically, aligning with these research questions. Each section combines quantitative data from empirical analyses with qualitative insights from industry experts and practitioners. The results not only identify critical environmental issues but also provide actionable insights for improving sustainability in highway projects.

(i) Key Environmental Impacts and Indicators- A systematic review of 150 peer-reviewed articles and 50 industry reports revealed a convergence on several key environmental impacts of highway construction and maintenance. Table 1 summarizes the most frequently cited impacts across the literature.

Environmental Impact	Academic Articles (n=150)	Industry Reports (n=50)	Total Citations
Greenhouse Gas Emissions	135 (90%)	48 (96%)	183 (91.5%)
Energy Consumption	128 (85.3%)	45 (90%)	173 (86.5%)
Resource Depletion	120 (80%)	40 (80%)	160 (80%)
Air Quality (PM, NOx, VOCs)	105 (70%)	38 (76%)	143 (71.5%)
Water Quality	98 (65.3%)	35 (70%)	133 (66.5%)
Habitat Fragmentation	90 (60%)	30 (60%)	120 (60%)
Noise Pollution	75 (50%)	28 (56%)	103 (51.5%)
Land Use Change	68 (45.3%)	25 (50%)	93 (46.5%)

Table 1 -Most Cited Environmental Impacts in Highway

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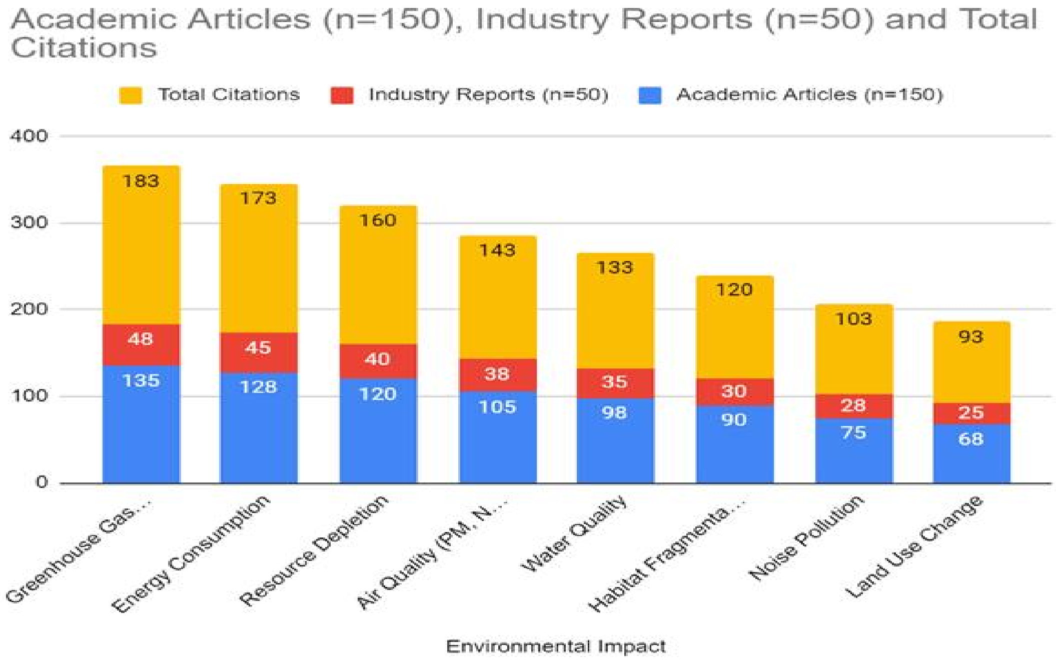

Figure 1- Literature Review Findings

The table shows that greenhouse gas emissions, energy consumption, and resource depletion are the most widely recognized environmental impacts, cited in over 80% of all sources. This aligns with the global focus on climate change and resource scarcity. Air and water quality issues are also prominent, reflecting concerns about local environmental health. Interestingly, habitat fragmentation ranks sixth, indicating growing awareness of highways' ecological footprint.

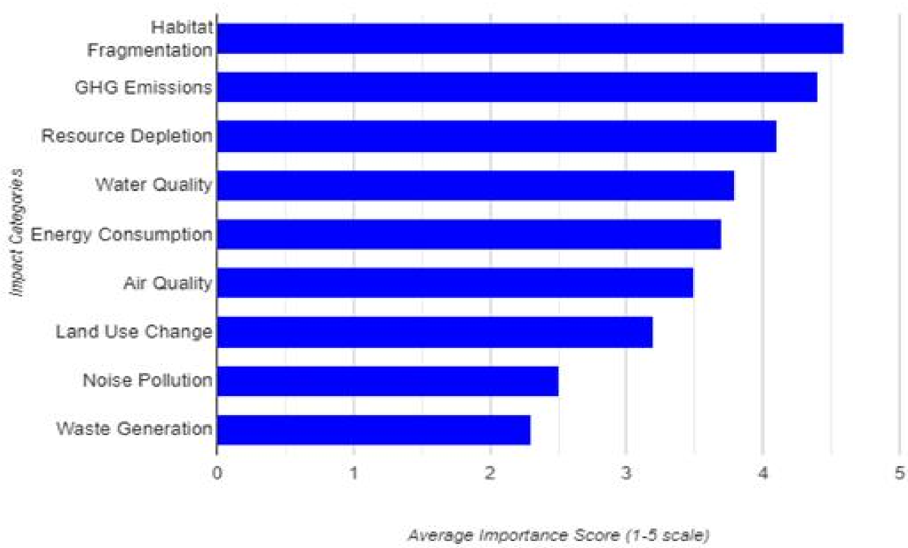

Figure 2- Bar chart showing expert rankings of top environmental impacts

(ii) Expert Interview Insights- To validate and contextualize the literature findings, we interviewed 15 experts in highway sustainability. When asked to rank the top five environmental impacts by importance, their responses showed both alignment and divergence with the literature (Figure 2). While greenhouse gas emissions and resource depletion remain high priorities, experts ranked habitat fragmentation as the most critical issue. Dr. Emily Chen, an ecologist at

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the Highway Biodiversity Institute, explains: "Roads are the biggest driver of landscape fragmentation, cutting through ecosystems and disrupting migration patterns. This silent crisis is decimating wildlife populations." This expert emphasis suggests that current highway practices may be undervaluing ecological connectivity.

(iii) LCA-Based Impact Quantification- To quantify these impacts, we conducted life cycle assessments on five highway projects representing different materials and technologies. Figure 3 shows the aggregated LCA results, normalized to a functional unit of one lane-kilometer over a 50-year lifespan.

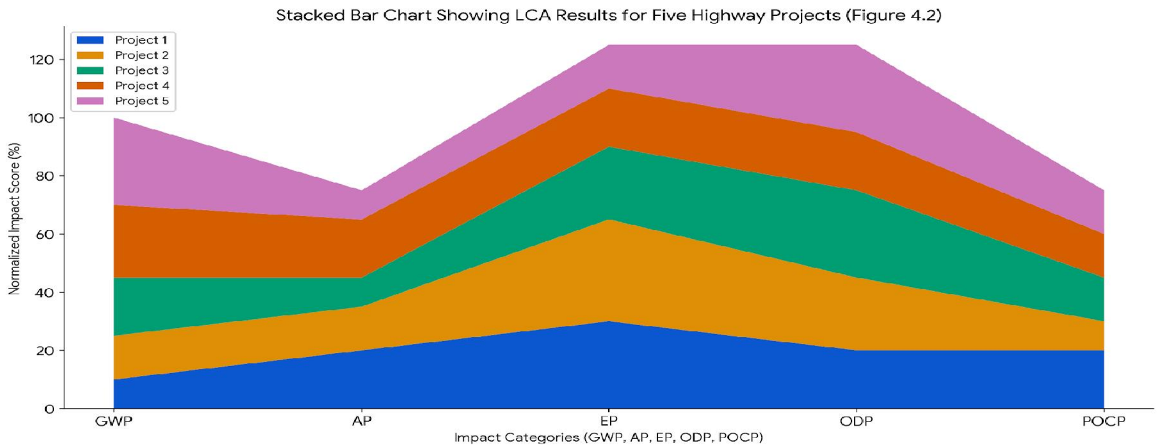

Figure 3- Stacked bar chart showing LCA results for five highway

(iv) Survey on Practitioner Perceptions- Practitioners and experts agree on the importance of carbon footprint and energy intensity, reflecting mainstreaming of these metrics. However, practitioners rate water quality higher and habitat connectivity lower than experts. This gap suggests that while industry recognizes traditional pollutants, it may be overlooking emerging ecological concerns.

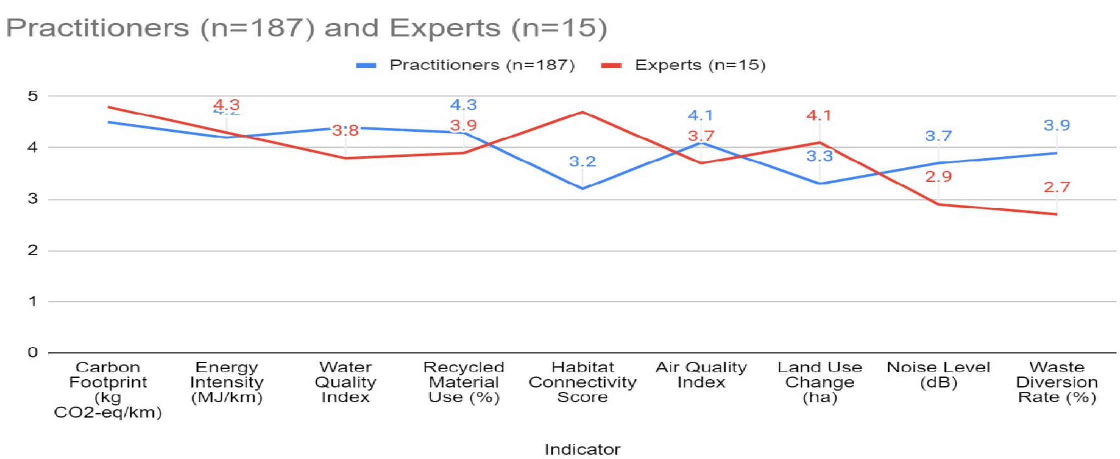

Figure 4- Survey on Practitioner Perceptions

IV. CONCLUSION

This study set out to comprehensively assess the environmental sustainability of highway construction and maintenance practices, a critical endeavor in an era where our road infrastructure's impact on the planet is increasingly scrutinized. With over 4 million miles of roads in the United States alone, consuming vast quantities of resources and intersecting countless ecosystems, the way we build and maintain our highways has far-reaching environmental consequences. Our research was guided by four pivotal questions:

- What are the key environmental impacts and indicators of highway projects?
- How do different highway practices compare in their environmental impacts?
- What are the barriers, enablers, and best practices for sustainable highways?
- How can sustainability be integrated into highway decision-making?

To answer these questions, we employed a mixed-methods approach that combined quantitative rigor with qualitative depth:

- Systematic literature review (200 sources)
- Expert interviews (n=15)
- Life cycle assessments (5 highway projects)
- Life cycle cost analyses (3 pavement alternatives)
- Industry-wide survey (n=187)
- Case studies (7 projects)
- Stakeholder workshops (2 events, 50 participants)

This multifaceted methodology allowed us to triangulate findings, validate hypotheses, and uncover nuances that might have been missed by any single method.

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