SYMBIOSIS

Impact Assessment Tools for Linear Infrastructures

Deliverable 3.1

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2	FEHRL	FORUM DES LABORATOIRES NATIONAUX EUROPEENS DE RECHERCHE ROUTIERE FEHRLAISBL	BELGIUM
3	UPM	UNIVERSIDAD POLITECNICA DE MADRID	SPAIN
4	CERTH	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS	GREECE
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20	UNIVLEEDS	UNIVERSITY OF LEEDS	UNITED KINGDOM
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EXECUTIVE SUMMARY

This report has been developed within the framework of the SYMBIOSIS project, as part of Task 3.1.1 of Work Package 3. It contributes to *Milestone 6: Internal report on the evaluation and enhancement of stakeholders' involvement in decision-making processes and transport policy formulation*, by providing a comprehensive overview of operational tools used to assess the environmental impacts and potential benefits of linear transport infrastructure projects.

The report combines two complementary analytical components. The first is a systematic literature review of over 100 case studies published between 2021 and 2024, which examines how current methodologies address ecological and biodiversity impacts throughout the full life cycle of transport infrastructure, from design and construction to operation, maintenance, and end-of-life. The second is a structured expert consultation conducted through a three-round Delphi study involving railway professionals from seven European countries, which captures the institutional, operational, and governance barriers that shape how, and whether, available tools are deployed in practice.

Each case study was analysed based on standardised criteria, including the nature of the assessed activity (service, plan, corporate strategy, or technical solution), life cycle stage, target audience, system boundaries, inventory data quality, and methodologies applied for impact and benefit assessment. Particular attention was given to tools and frameworks that consider biodiversity, ecological connectivity, habitat fragmentation, species loss, and pollution in terrestrial and aquatic ecosystems. The Delphi study complemented this analysis by surfacing the practitioner perspective on regulatory drivers, fiscal constraints, stakeholder conflicts, and knowledge gaps that the literature alone cannot capture.

Together, the two components reveal a sector operating under a compliance ceiling: regulation drives biodiversity action but simultaneously absorbs the resources that would enable going beyond the requirements of those regulations. While many studies employ advanced techniques, such as life cycle assessment (LCA), spatial modelling, ecological field monitoring, or environmental performance indicators, the integration of ecological qualities and biodiversity as central assessment criteria remains inconsistent. Moreover, structured benefit assessment frameworks are often lacking or underdeveloped, limiting the ability to capture positive outcomes or trade-offs. Expert consensus confirms that economic incentives aligned with environmental performance, rather than stronger regulation, represent the critical lever for exceeding minimum compliance thresholds.

This report provides critical insights for the development of integrated, transparent, and comparable tools that support the inclusion of ecological and biodiversity dimensions in linear infrastructure planning and decision-making. It reinforces the role of robust environmental assessment in strengthening stakeholder engagement and enhancing evidence-based transport policy across Europe, in alignment with the European Union Biodiversity Strategy for 2030 and the Kunming-Montreal Global Biodiversity Framework.

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GLOSSARY OF TERMS

Baseline scenario	A reference situation used as a benchmark to assess the environmental impacts or benefits of a proposed project or intervention. It typically reflects a "business-as-usual" condition without the implementation of mitigation or enhancement measures.
Blue infrastructure	Water-related components of infrastructure that support ecosystem functions and climate regulation, such as rivers, lakes, wetlands, canals, and sustainable urban drainage systems.
Building Information Modelling (BIM)	A digital process that integrates data, technology, and workflows to improve the planning, design, construction, and management of infrastructure assets. BIM supports decision-making throughout the full life cycle, including renovation, maintenance, and decommissioning.
Carbon footprint	An indicator that measures the total greenhouse gas emissions caused directly or indirectly by an activity, product, or entity, usually expressed in terms of carbon dioxide equivalents (CO_2e).
Delphi Technique	A structured elicitation method that gathers and synthesizes expert judgement through successive rounds of questionnaires, with controlled feedback between rounds. Participants revise their assessments iteratively in light of the group's responses, converging towards a consensus view. It is commonly applied in environmental and impact assessment contexts to prioritise indicators, define criteria, or address areas where empirical data are limited or uncertain.
Ecological connectivity	Description of the degree to which movement between different resources or habitats is possible or not possible within a landscape. Ecological connectivity supports species migration, genetic exchange, and the resilience of ecosystems.
Ecosystem functions	The biological, geochemical, and physical processes and interactions—such as nutrient cycling, pollination, and energy flow—that sustain and regulate an ecosystem
Ecosystem services	The benefits that humans derive from ecosystems, including provisioning, regulating, cultural, and supporting services.
Environmental footprint	A methodology developed by the European Commission to assess and communicate the potential environmental impacts of products and organizations throughout their life cycle, based on Life Cycle Assessment principles.
Environmental Impact	A project-level process used to identify, predict, and evaluate the environmental and social impacts of proposed developments. It supports informed decision-making by

Assessment (EIA)	assessing both positive and negative effects, exploring alternatives, and recommending mitigation measures. EIA has led to specialized tools such as social impact assessment, biodiversity impact assessment, and strategic environmental assessment (SEA).
Green infrastructure	A strategically planned network of natural and semi-natural areas, including vegetation-based solutions, designed to deliver ecosystem services and enhance biodiversity.
Grey infrastructure	Conventional built infrastructure such as roads, railways, bridges, drainage systems, and flood barriers, typically engineered with concrete, asphalt, or metal materials.
Habitat fragmentation	The division of larger, continuous habitats into smaller, isolated patches, often due to linear infrastructure, which can reduce biodiversity and disrupt ecosystem functioning.
IPCC	(Intergovernmental Panel on Climate Change) The principal international scientific body established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to assess the state of knowledge on climate change, its causes, potential impacts, and response options. The IPCC produces periodic assessment reports that synthesize scientific evidence and serve as the primary reference for international climate policy.
Life Cycle Assessment	A systematic method for evaluating the environmental impacts of a product, process, or system throughout its entire life cycle — from raw material extraction to disposal — based on ISO 14040/44 standards.
Monetization Frameworks	Structured methodologies used to assign monetary values to environmental and social impacts, enabling their integration into economic appraisals, cost-benefit analyses, and natural capital accounting. Common approaches include valuation techniques such as willingness to pay, replacement cost, and hedonic pricing, as well as standardized value transfer methods used in policy and infrastructure assessment contexts.
Monetization of impacts	The process of expressing environmental impacts in monetary terms, often used in cost-benefit analysis or natural capital accounting.
Natural Capital	The stock of natural assets, including soils, water, air, geology, and living organisms — from which humans derive a wide range of ecosystem services and economic benefits. Natural capital accounting frameworks seek to make the value of these assets visible in decision-making, complementing traditional financial accounts by quantifying the depletion or enhancement of nature over time.

Nature-based Solutions	Actions that protect, sustainably manage, and restore natural or modified ecosystems to address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.
Operational tool	A method, model, software, or framework that is actively used in planning, designing, or assessing infrastructure, with practical applicability in real-world decision-making contexts.
Scoping	An early step in environmental assessment that defines the scope and key focus areas of the study, including geographic boundaries, temporal scale, and environmental parameters to be considered.
Screening	The process of determining whether a project requires a full Environmental Impact Assessment, typically based on project characteristics, location, and potential environmental risks.
Sensitivity analysis	A technique used to determine how the variation in outputs of a model or assessment can be attributed to different input variables, useful for evaluating uncertainty and robustness.
Strategic Environmental Assessment	A systematic process for evaluating the environmental effects of policies, plans, or programmes before their formal adoption, typically applied at a higher decision-making level than project-specific EIAs.

INTRODUCTION

The SYMBIOSIS project addresses one of the central challenges in sustainable infrastructure development: how to systematically integrate biodiversity and environmental considerations into the planning, construction, and management of linear transport infrastructure. Funded by Europe's Rail Joint Undertaking under the Horizon Europe programme, the project brings together a consortium of European research institutions, railway operators, and environmental specialists to advance tools, methods, and guidance that support biodiversity-sensitive decision-making across the full infrastructure life cycle. Work Package 3 (Operational Toolkit) sits at one of its core intersections: its overarching goal is to review and develop a set of operational tools that adopt a holistic approach, integrating environmental, biodiversity, and carbon dimensions into the management of railway infrastructure and its associated energy systems.

Within WP3, Task 3.1 serves as the analytical foundation for the entire package. Before tools can be developed, improved, or recommended, a thorough understanding of what exists, how it works, and where it falls short is required. Task 3.1 therefore undertakes a systematic exploration and characterisation of current operational tools used to assess ecological connectivity, environmental impacts, and biodiversity across all life cycle phases of linear infrastructure, from planning and design through construction, operation, maintenance, and end-of-life. Its outputs directly inform Task 3.4 (the Biodiversity-CO2 Calculator), provide methodological grounding for Tasks 3.2 and 3.3 (climate resilience mapping and Blue-Green Infrastructure guidance), and feed into the cross-cutting policy recommendations developed in WP5.

This deliverable, D3.1, responds to a concrete gap of vital importance for the project. While numerous impact assessment tools exist in the transport sector, no systematic, multi-dimensional characterisation of their scope, methodological approach, and fitness for biodiversity-sensitive railway planning had been produced in recent years. Existing reviews tend to focus on single infrastructure modes, isolated life cycle phases, or specific impact categories, and rarely integrate the practitioner perspective on what barriers prevent available tools from being effectively deployed. D3.1 addresses this gap through two complementary analytical components, a systematic literature review of over 100 case studies published since 2021, and a structured three-round Delphi study involving railway professionals from across Europe.

The report is structured as follows. Section 1 sets out the specific objectives of the deliverable. Section 2 describes the methodology applied in both the literature review and the Delphi study, including the analytical framework, research questions, and screening criteria. Section 3 presents the results of the literature review, organised around seven analytical dimensions. Section 4 draws conclusions and formulates recommendations emerging from the review. Section 5 presents the Delphi study, its rationale, methodology, key findings, and implications for SYMBIOSIS. Supporting materials, including the full case study database and the Delphi questionnaire, are provided in the Annexes.

Partner Contributions to D3.1

Partner	Specific contributions
UPM	Led the development of D3.1 as Task Leader, coordinating the methodological framework and overall structure of the deliverable. Conducted a systematic review of existing operational tools and assessment frameworks applicable to railway biodiversity and climate resilience. Coordinated stakeholder engagement with infrastructure managers, operators, and research partners, and synthesised findings into the requirements framework guiding the development of subsequent WP3 tools.
UKCEH	Supported the review of existing ecological assessment approaches applicable to transport infrastructure contexts and contributed scientific expertise on biodiversity indicators and monitoring frameworks. Contributed to railway sector perspectives by supporting the use of case studies from surveys of railway stakeholders, helping identify operational needs and challenges related to biodiversity and climate considerations. Engaged actively in coordination activities with WP4 to ensure alignment between tool requirements and biodiversity monitoring developments.
SLU	Provided scientific expertise on biodiversity monitoring and habitat connectivity assessment, drawing on extensive experience in Scandinavian railway corridor research. Supported the review of existing tools and standards applicable to ecological management along linear transport infrastructure, contributing to the identification of requirements for biodiversity-sensitive operational tools.
FFE	Contributed railway sector expertise to the identification of user needs and data availability conditions within the railway value chain. Participated in WP3 coordination meetings, providing operational insights from infrastructure management practice and supporting alignment of the requirements framework with real-world implementation contexts.
MINUARTIA	Contributed with biodiversity and nature-based solutions expertise to the requirements analysis, supporting the identification of ecological requirements and practical implementation considerations drawn from environmental consultancy experience. Participated in WP3 coordination meetings and provided alignment with Task 3.2 activities.
CERTH	Contributed expertise on societal and governance dimensions to ensure alignment of the toolkit requirements with policy frameworks and end-user needs. Actively engaged in planning and coordination meetings, contributing to the definition of methodological requirements for the operational tools.
UNIVLEEDS	Ensured transport research expertise to the requirements analysis, with a focus on decision-support frameworks and stakeholder engagement approaches. Engaged in planning and coordination meetings, supporting the review of methodologies relevant to sustainable transport planning.

1. OBJECTIVES

The overarching aim of this task is to support the development of harmonised, evidence-based tools that can be used by infrastructure managers, planners, and policymakers to assess and mitigate the impacts of linear transport infrastructure on ecological systems and biodiversity throughout all life cycle phases.

In this context, the specific objectives of the current deliverable are organised around four thematic clusters (See Figure 1).

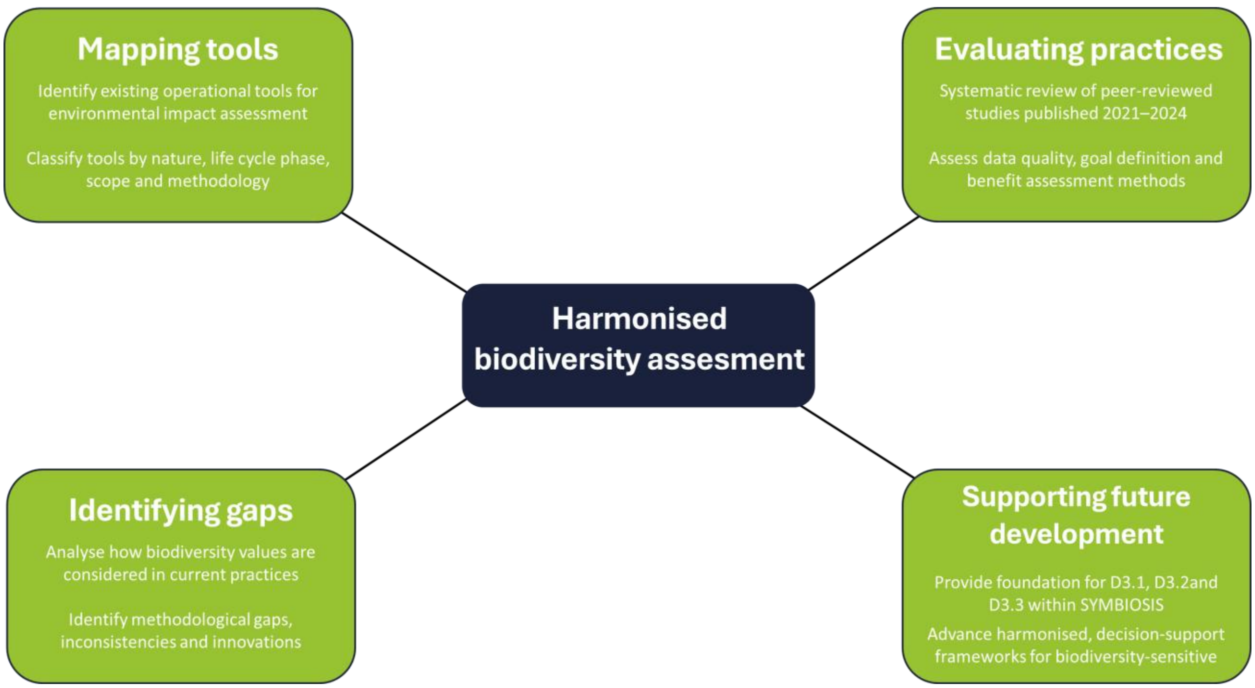

Figure 1: Thematic clusters of the deliverable's objectives.

Mapping tools. The deliverable aims to identify and characterise existing operational tools used for environmental impact and benefit assessment in the context of linear infrastructure, with a particular focus on tools that integrate biodiversity and ecological criteria, and to assess current scientific practices through a systematic review of peer-reviewed studies published between 2021 and 2024, focusing on how biodiversity and ecological impacts of linear infrastructure are addressed across different research approaches and contexts.

Evaluating practices. The deliverable seeks to classify the reviewed tools and approaches according to the following analytical dimensions: nature of the activity (strategic, operational, or solution-oriented); life cycle phase addressed (design, construction, operation, maintenance, end-of-life); definition of assessment goals and target audience; scoping and system boundaries; data inventory quality and transparency; methodologies used for environmental impact assessment (e.g., IPCC, Environmental Footprint, Natural Capital, monetization frameworks); and methods for benefit assessment and identification of baseline criteria.

Identifying gaps. The deliverable aims to analyse the extent to which biodiversity values and ecological functions are explicitly considered in current assessment practices, and to identify methodological gaps, inconsistencies, or areas of innovation.

Supporting future development. Finally, the deliverable seeks to provide a foundation for future development of integrated tools and guidance within SYMBIOSIS, particularly in Deliverables D3.2 and D3.3, which aim to advance harmonised methodologies and decision-support frameworks for biodiversity-sensitive transport infrastructure.

2. METHODOLOGY

This deliverable draws on two complementary methodological components. The first is a systematic literature review of peer-reviewed case studies, designed to characterise current tools and practices for environmental impact assessment in linear infrastructure. The second is a structured expert consultation conducted through a Delphi study, designed to capture the practitioner perspective on the barriers and enablers that determine whether available tools are effectively deployed in operational contexts. Together, these two components provide both bibliometric evidence and primary expert knowledge to address the objectives set out in Section 1.

2.1. LITERATURE REVIEW: SEARCH STRATEGY, SELECTION AND SCREENING

The literature review aimed to identify relevant case studies and methodological approaches used to assess the environmental impacts and benefits of linear infrastructure, with a particular emphasis on ecological and biodiversity aspects. The search was conducted during 2025 and targeted academic and technical literature published between 2021 and 2024, with the objective of capturing both methodological developments and applied experiences. This time frame was selected to ensure the inclusion of the most recent research insights available, reflecting current practices, innovations, and emerging trends in the field.

The selection process focused primarily on peer-reviewed scientific publications (n=98), given their methodological rigour and thematic depth — particularly those addressing environmental impact assessment tools and ecological evaluation methods applied across different infrastructure life cycle phases.

The screening process followed two main stages:

- Initial screening of titles and abstracts to eliminate irrelevant topics (e.g., building infrastructure, urban planning, or general environmental assessments without a clear link to linear infrastructure or biodiversity);
- Full-text screening of the remaining documents, based on the following inclusion criteria:
- Relevance to linear infrastructure (transport or analogous sectors);
- Inclusion of environmental and/or biodiversity impact or benefit assessment;
- Use or description of a structured tool, method, or operational framework.

Search terms combined concepts such as "linear infrastructure", "environmental impact", "life cycle assessment", and "case study", with results filtered based on thematic focus, methodological detail, and overall relevance to the objectives of Task 3.1.1.

In addition to academic sources, the review included a minority of technical documents (n=4) corresponding to recent Environmental Impact Assessments (EIAs) for railway infrastructure projects in European countries. Although not published in scientific journals, these cases provide valuable insights into the real-world application of operational tools under current regulatory and planning frameworks.

It is worth noting that the predominance of scientific literature introduces a potential bias toward narrowly focused or theoretical approaches, which may not fully reflect the complexity of practical decision-making contexts. Publication bias toward well-documented or successful cases may lead to underrepresentation of negative or incomplete assessments. Similarly, tools developed for non-transport linear infrastructure were included when relevant but may reflect sector-specific constraints or assumptions.

A full overview of the 102 case studies examined, including classification and key methodological features, is provided in Annex I.

2.2. EXPERT ASSESSMENT: DELPHI STUDY

The systematic literature review provides a comprehensive characterisation of how current tools address ecological and biodiversity impacts across the life cycle of linear transport infrastructure. This section complements it by capturing the perceptions and decision-making processes of railway practitioners who possess expert knowledge that may be underrepresented in the published literature. Where the literature review characterises formal and published practice, the Delphi study surfaces the institutional constraints, organisational priorities, and governance frictions that shape how available tools are actually deployed in operational contexts. This distinction is methodologically significant: gaps identified in the literature may reflect not an absence of knowledge, but an absence of conditions under which that knowledge can be applied.

As such, a three-round Delphi study was conducted to assess expert consensus on the barriers hindering effective biodiversity integration in European railway operations. The Delphi approach was selected for its demonstrated effectiveness in environmental management and transportation research contexts, and its particular suitability for generating structured consensus when empirical evidence is incomplete or fragmented, conditions that characterize the current state of biodiversity integration practice across the sector, according to the report's previous findings.

A panel of eight railway professionals with expertise in biodiversity and environmental management was assembled, representing seven EU member states: Austria, France, Great Britain, Italy, Portugal, Spain, and Sweden. The multistakeholder composition, spanning passenger operators, infrastructure managers, academics, and network managers, was prioritized over panel size in order to maximize institutional and geographic diversity within the available expert pool. Round 3 was completed by six of the eight panel members.

The three rounds were structured to progressively narrow the scope of inquiry from open exploration to definitive quantitative assessment:

- **Round 1** comprised ten open-ended questions designed to explore broad patterns and identify key areas of divergence across the expert group.
- **Round 2** introduced Likert-scale, close-ended, multiple-choice, and matrix questions to enable quantitative prioritization and consensus measurement. A consensus threshold of 75% (6/8 respondents) was applied.
- **Round 3** consisted exclusively of close-ended questions to achieve definitive consensus assessment on topics where divergence persisted. A threshold of 67% (4/6 respondents) was applied to reflect the reduced panel size.

In cases where the threshold yielded a fractional respondent count, it was rounded down to the nearest whole number to avoid inadvertently raising the effective consensus requirement beyond the predetermined level.

3. RESULTS AND DISCUSSION

This section presents the findings of the two analytical components of this deliverable. Sections 3.1–3.9 synthesise the results of the systematic literature review, drawing on 102 case studies published across journals in environmental science, transport research, ecological modelling, life cycle assessment, and biodiversity conservation. Section 3.10 complements these findings with the results of the structured expert consultation.

The review was structured around the following key questions:

- **Operational tools in use:** Which operational tools are currently used to assess ecological and biodiversity impacts of linear infrastructures?
- **Distribution across the life cycle**: How are these tools distributed across the infrastructure life cycle (design, construction, operation, maintenance, renewal)?
- **Applied methodologies**: What methodologies are applied for environmental impact and benefit assessment?
- **Integration of biodiversity and ecological functions:** To what extent are biodiversity values and ecological functions incorporated explicitly?

To address these questions, each case study was analysed according to four analytical dimensions:

1. **Scope and application context covering the life cycle phase**, the purpose of the assessment together with its targeted audience.
2. **System definition and data robustness** covering the definition of system boundaries, the scoping practices adopted, and the transparency and quality of inventory data used within the assessment process.
3. **Impact assessment methodology** covering the specific methodological approaches applied to evaluate environmental impacts, including the models, indicators, and calculation procedures.

4. **Benefit assessment and baseline definition** (where applicable), covering how environmental benefits are assessed, including the definition of baseline scenarios and the criteria used for comparison.

These four dimensions are operationalised across Sections 3.2–3.9 as follows: scope and application context is addressed through the nature of activities (§3.2), life cycle phases (§3.3), and target audience (§3.4); system definition and data robustness through scoping practices (§3.5) and inventory data (§3.6); impact assessment methodology through the impact assessment methods reviewed (§3.7); and benefit assessment and baseline definition through the benefit assessment methods documented (§3.8). Section 3.1 provides the geographic context for the full dataset, and Section 3.10 presents the expert consultation findings.

3.1. CASE STUDIES BY REGION

The reviewed studies encompass considerable geographic diversity (Figure 2). Most originate from Europe (49), followed by Asia (28), South America (8), North America (5), and Africa (2). Additionally, ten (10) case studies adopted a transnational or multiregional approach. This geographic coverage allows for the inclusion of a wide range of ecological contexts, legislative frameworks, and technical capacities, thereby enriching the transferability and adaptability of the review's findings.

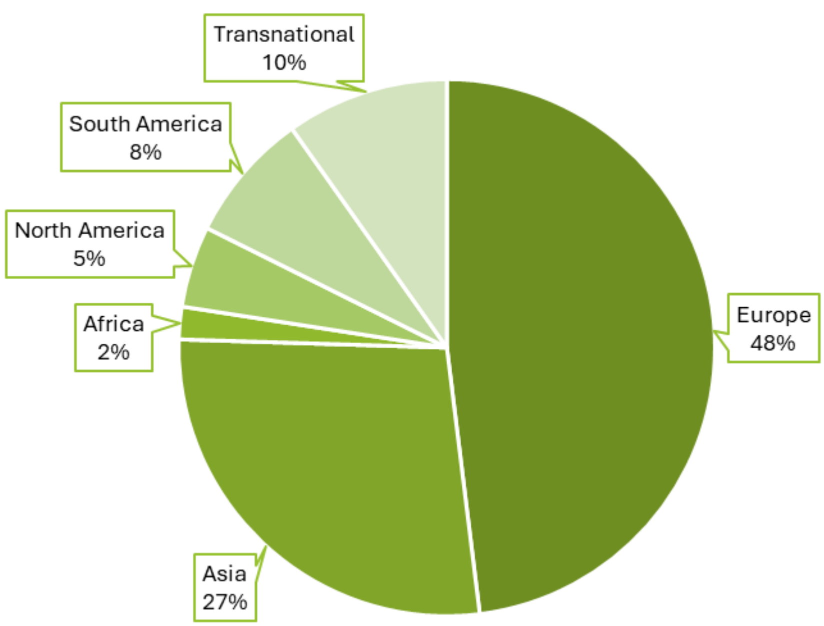

Figure 2: Regional distribution of the reviewed case studies, showing a strong concentration in Europe (48%) and Asia (27%), while Africa, North America, and South America remain comparatively underrepresented; detailed case references are provided in Annex I.

This geographic concentration has methodological implications for the transferability of the review's findings. The strong representation of European and Asian contexts reflects differences in regulatory maturity, institutional capacity, and research funding availability across regions. Studies from Africa, North America, and South America remain comparatively underrepresented, which may introduce a bias toward regulatory frameworks and ecological contexts that are not universally applicable. Findings related to tool design, scoping practices, and assessment methodologies should therefore be interpreted with this geographic skew in mind, and future reviews should explicitly seek to incorporate evidence from underrepresented regions to strengthen the global applicability of emerging frameworks.

3.2. NATURE OF THE ACTIVITIES

Understanding the nature of the activities addressed in the case studies is essential to interpreting how biodiversity considerations are integrated into transport infrastructure. The following four categories represent an analytical framework to better capture the functional orientation of each case study. They are based on the purpose and methodological focus of the study rather than the generic sector or topic label used in the case study sheets in ANNEX I.

The 102 case studies were grouped into four main categories based on the nature of the activity (

Figure 3):

1. **Specific solutions (53 cases; ~52%):** This includes technical assessments and mitigation measures applied to specific infrastructure components, such as wildlife crossings, noise barriers, drainage systems, or material comparisons. These studies are characterized by a high level of technical detail and are usually implemented in real-world settings. Their focus is operational, often involving life cycle tools or performance-based evaluations aimed at continuous improvement.

2. **Plans or strategies (41 cases; ~40%):** This category includes regional strategies, ecological integration guidelines, and planning tools—particularly common in the European context. These activities are typically implemented in early stages of infrastructure development, aiming to prevent ecological harm and embed biodiversity at broader spatial and governance scales. While not always grounded in quantitative metrics, their influence on policy and planning is potentially considerable.

3. **Services (10 cases; ~10%):** This category encompasses environmental monitoring, ecological indicator tracking, and operational performance evaluations. These studies tend to focus on information provision rather than direct intervention, offering valuable insights into ecosystem quality during the use phase of infrastructure, but often without being tied to a specific project.

4. **Corporate frameworks (8 cases; ~8%):** This includes methodologies and reference tools developed by agencies, institutions, or international consortia. These initiatives aim to standardize approaches and provide replicable frameworks for ecological assessment. Rather than addressing a single infrastructure asset, they support integrated environmental governance at organizational or systemic levels.

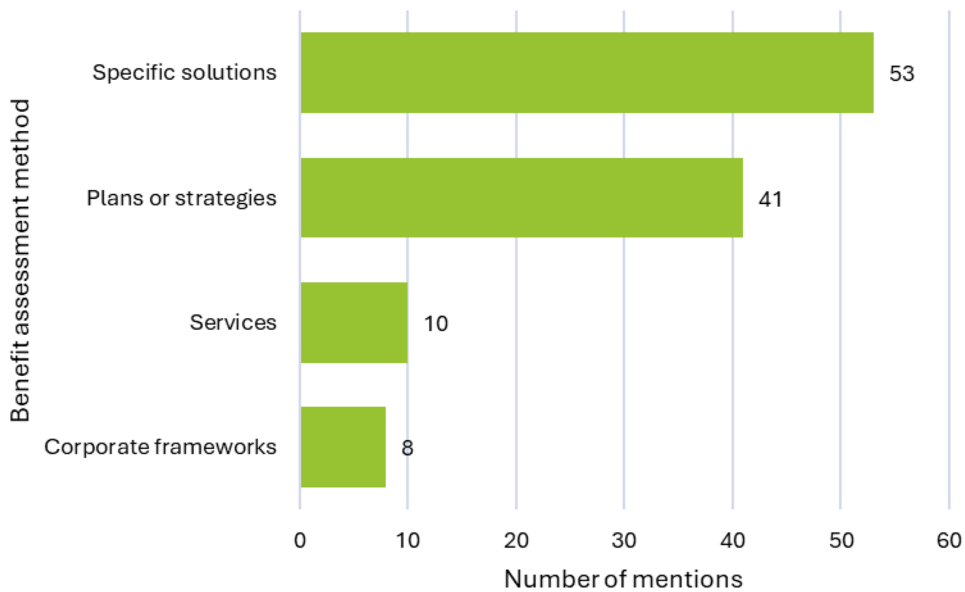

Figure 3: Distribution of case studies by nature of the assessed activity, showing the predominance of specific technical solutions and planning or strategic interventions over service-oriented and corporate framework applications.

3.3. LIFE CYCLE PHASES

Understanding which life cycle phases are addressed in biodiversity-related assessments of linear infrastructure is essential for evaluating both the scope and robustness of these studies. Each phase presents distinct ecological challenges and opportunities, and the methodological approaches used vary accordingly. While some case studies adopt a comprehensive cradle-to-grave or cradle-to-gate perspective, particularly those employing formal LCA, any others remain focused on specific stages, often driven by data availability, project priorities, or institutional mandates.

A clear relationship also emerges between the life cycle phases addressed and the nature of the activities identified in the previous section. Plan- and strategy-oriented studies are predominantly concentrated in the planning and design phase, where biodiversity considerations can be embedded through corridor selection, ecological zoning, and avoidance measures. By contrast, studies focused on specific technical solutions tend to concentrate on construction and operation, where direct impacts such as land take, emissions, wildlife collisions, or habitat disturbance are most visible and measurable. Service-oriented activities are more commonly associated with operation and maintenance, particularly through monitoring, ecological indicators, and performance evaluation. Finally, corporate frameworks often adopt a cross-cutting perspective that can span multiple phases, although in practice they are most frequently linked to planning and governance functions. This alignment helps explain why certain life cycle phases receive more methodological attention than others.

Overall, the analysis reveals a fragmented assessment landscape, with certain phases consistently emphasized (especially operation and construction), and others, such as maintenance and end-of-life, underrepresented (Figure 4). Note that case studies often deal with more than one phase, hence the mentions sum to more than 102. Expanding methodological coverage across all life cycle phases would enhance the ability to address long-term and cumulative ecological impacts.

1. **Planning and design phase (43 studies; 42%):** This phase is crucial for setting the foundation for environmentally responsible infrastructure. It includes early-stage evaluations such as ecological corridor mapping, sensitivity analyses, and strategic sitting decisions. Studies in this phase are generally forward-looking and aligned with regulatory planning frameworks. They often emphasize avoidance measures in line with the mitigation hierarchy but may lack the granularity of operational assessments.

2. **Construction phase (70 studies; 69%):** This phase includes assessments of direct impacts such as land clearance, noise from heavy machinery, air pollution, and disruption of local ecosystems. It is also a key focus for studies employing LCA tools or comparing material alternatives. Construction-related assessments often emphasize the need for real-time environmental monitoring and adaptive management practices to mitigate immediate ecological damage.

3. **Operation phase (80 studies; 78%):** This is the most frequently addressed phase. Case studies in this category commonly assess environmental pressures related to active infrastructure use, such as traffic emissions, noise, wildlife collisions, and habitat degradation. Many also apply ecological monitoring, bioindicators, or remote sensing tools to evaluate long-term impacts. While the operational phase provides valuable insights into persistent effects, the evaluation of mitigation to measure effectiveness is often constrained by the lack of pre-implementation data and proper control comparisons. Robust assessments typically require a BACI (Before-After-Control-Impact) design, which remains underused in most reviewed studies.

4. **Maintenance phase (54 studies; 53%):** This phase receives moderate attention, though still insufficient considering its potential cumulative impacts over the infrastructure's lifespan. Studies that include maintenance often focus on recurring emissions, wear-related material degradation, and vegetation management. However, few incorporate systematic modelling of maintenance schedules, highlighting a need for greater methodological integration in this area.

5. **End-of-Life phase (38 studies; 37%):** This remains the least addressed phase. Where considered, it typically involves material recovery, demolition waste management, or infrastructure repurposing. Despite its limited coverage, this phase holds significant potential for reducing long-term ecological footprints and indirect impacts, especially through the reuse of construction materials and the application of sustainable decommissioning practices. These in turn could reduce wider biodiversity impacts, for example, through reducing the amount of aggregate extraction required for subsequent construction. Its underrepresentation highlights the need for better data availability and more robust methodological frameworks to support integration into life cycle-based assessments.

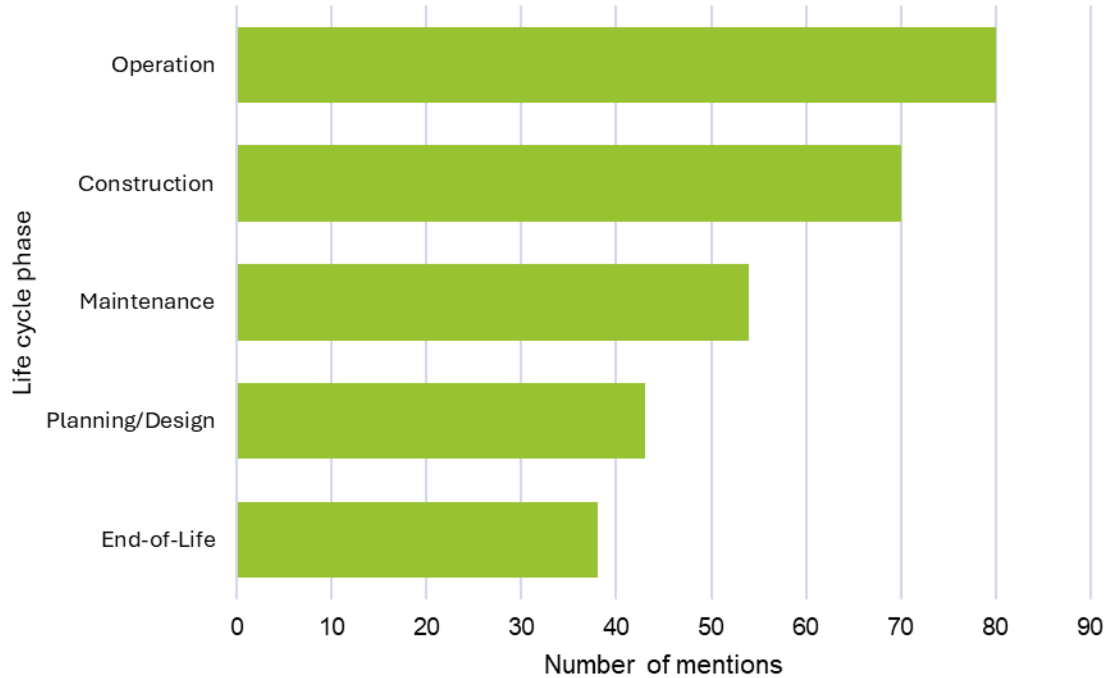

Figure 4: Frequency of life cycle phases covered in the reviewed case studies, highlighting the strong emphasis on operation and construction phases, while planning/design and end-of-life remain comparatively less represented.

3.4. TARGET AUDIENCE

The analysis of the target audiences addressed in the reviewed case studies underscores the critical role of tailoring environmental assessments to meet the specific needs of decision-makers, practitioners, and stakeholders. The effectiveness of integrating biodiversity into infrastructure planning and management depends not only on methodological soundness but also on the degree to which results are accessible, relevant, and actionable for the intended users.

Target audience definition varied widely depending on the study's scope, the infrastructure life cycle phase, and whether the focus was technical, regulatory, or community-oriented. The studies published in high-impact scientific journals (e.g. Journal of Cleaner Production, Science of the Total Environment, The International Journal of Life Cycle Assessment, Environmental Pollution or Environment, Development and Sustainability) were particularly valuable, as they (i) clearly identified a target audience from the outset, (ii) formulated problem-driven objectives aligned with that audience's mandate, and (iii) translated findings into practical tools, design guidelines, or policy inputs.

1. **Academic and scientific audience (96 studies; 94%):** Since scientific publications were prioritized in the literature search, a significant majority of studies targeted the academic and scientific community. These studies typically aimed to advance methodological innovation in biodiversity assessment, transport ecology, and predictive modelling. Their contributions included the

development of spatial tools, indicators, and integrative frameworks grounded in evidence-based research. These outputs often supported the conceptual evolution of biodiversity integration practices and contributed to peer-reviewed literature and technical capacity-building.

2. **Transport agencies and infrastructure managers (58 studies; 57%):** These studies focused on technical aspects such as noise reduction, ecological connectivity, construction materials, and maintenance optimization. Their results were generally operational in nature, offering practical guidance for improving environmental performance during planning, construction, and operational phases.

3. **Policy makers and environmental authorities (57 studies; 56%):** These cases addressed national ministries, regional administrations, and EU-level institutions, often presenting regulatory recommendations, harmonized indicators, or best-practice frameworks. A strong emphasis on regulatory alignment and policy guidance was observed in European case studies, particularly those connected to biodiversity mainstreaming strategies.

4. **Environmental planners and consultants (55 studies; 54%):** These cases often provided applied tools, modelling approaches, and decision-support systems intended to be used in the preparation of SEA/EIA documentation or in mitigation strategy design.

5. **Infrastructure engineers and developers** working on the physical design and implementation of transport infrastructure. **(53 studies; 52%):** These studies prioritized practical, solution-oriented outputs with direct implications for design optimization and sustainability performance.

6. **EIA/SEA practitioners and experts (32 studies; 31%):** Their role as translators between ecological science and project development was supported through guidance documents and assessment methodologies grounded in both qualitative and quantitative approaches.

7. **Conservation and biodiversity experts (17 studies, 17%):** These cases often focused on habitat protection, species impact analysis, and ecological monitoring. Their technical outputs are highly relevant for guiding mitigation design and setting ecological baselines.

8. **Local stakeholders & NGOs (13 studies; 13%):** These studies emphasized transparency, public engagement, and the co-creation of assessment criteria or mitigation options. There is an emerging trend to strengthen the inclusion of social dimensions in ecological infrastructure planning.

An overarching observation is the tendency to address multiple audiences simultaneously (hence the number of mentions in Figure 5 is >102), especially in studies funded by international consortia or focused on transnational corridors. These hybrid cases combine scientific rigor, technical relevance, and policy applicability, contributing to more integrative and actionable outcomes.

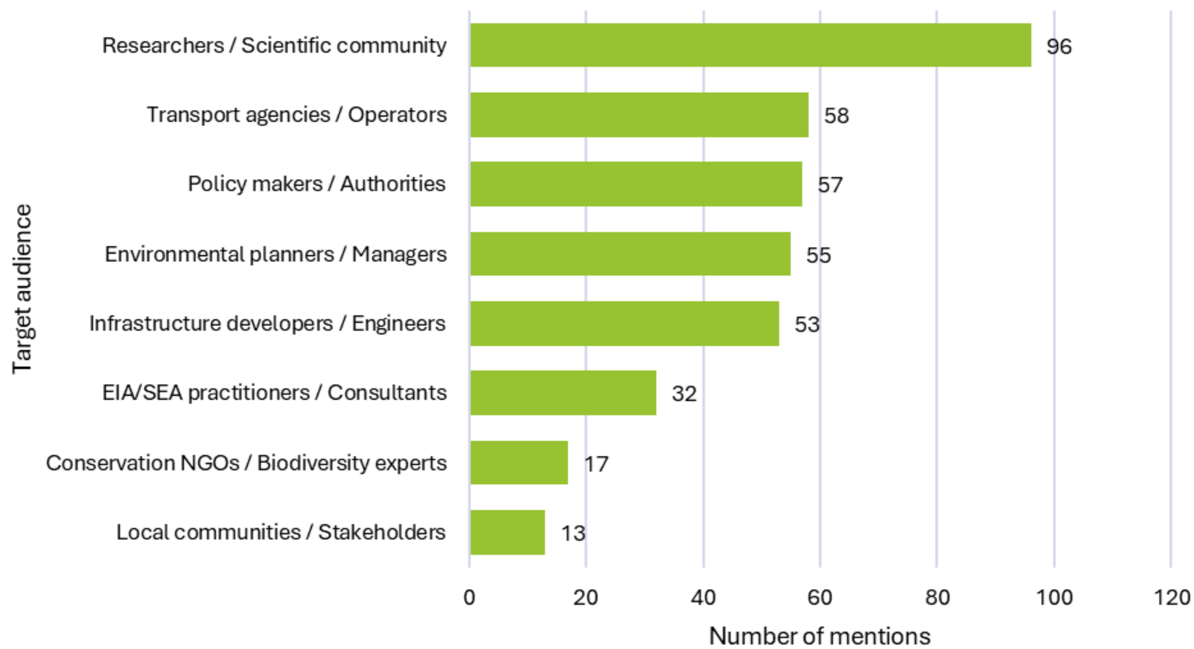

Figure 5: Distribution of target audiences across the reviewed case studies, indicating a strong orientation toward the scientific community, transport operators, and policy-related stakeholders, with limited direct focus on local communities and biodiversity NGOs.

It is worth noting that the predominance of academic audiences reflects a methodological assumption applied consistently across the review: studies that did not explicitly identify a target audience were classified as addressing the scientific community by default. This may overrepresent academic audiences relative to what the tools themselves were designed for in practice, and should be considered a limitation when interpreting the distribution shown in Figure 4.

3.5. SCOPING

The definition of system boundaries across the analysed case studies reveals marked heterogeneity, significantly influencing clarity, comparability, and applicability of assessment results. Although some studies adopt explicit LCA frameworks with well-defined analytical limits, the majority operate with partial or non-standardized scoping approaches, reflecting differences in purpose, disciplinary traditions, and spatial or institutional scale.

A clear dichotomy emerges between strategy-oriented studies, which rely on spatial or governance-based delineations, and technically detailed studies, which apply structured inventories and life cycle logic. Bridging this methodological divide remains a priority for the development of integrative tools that aim to assess ecological impacts across infrastructure types and governance levels.

1. **Strategic or territorial scoping (28 studies; 28%):** These approaches defined system boundaries in spatial, jurisdictional, or ecological terms rather than in relation to material or energy flows (Figure 6). They are typically used in planning frameworks, connectivity models, or biodiversity strategies that map areas of intervention (e.g., green corridors, protected zones) without quantifying environmental loads. While they are valuable for regional planning and policy design, they often lack technical specificity, which limits replication or integration into operational environmental assessments.

2. **Partial empirical scoping (non-LCA) (50 studies; 49%):** This is the most common approach based on project-specific observations such as field monitoring, or environmental sampling or local measurements (e.g., noise levels, air quality, species movement). Boundaries are defined pragmatically according to project-specific needs (e.g. spatial and temporal boundaries) . Although they produce valuable localised insights, they often fall short in methodological transparency with limited justification of system boundaries, weak baseline definitions and or insufficient consideration of system-wide interactions. This hinders their utility for broader decision-making or scenario comparison.

3. **Defined system boundaries under LCA methodology (24 studies; 24%):** These studies explicitly apply life cycle principles, with clearly defined system limits (e.g. "cradle-to-gate" or "cradle-to-grave"), functional units, allocation rules, and cut-off criteria. Often aligned with ISO 14040/14044 standards, they cover multiple infrastructure phases, particularly construction and operation. This approach offers the highest degree of methodological rigor and comparability, making them suitable for benchmarking, policy support, or investment evaluation.

Across all scoping approaches, several recurring gaps were noted in system boundary definition:

- **Limited inclusion of life cycle phases**: Maintenance and end-of-life phases are frequently excluded. Even in cases labelled as "cradle-to-grave", the coverage of the use phase is sometimes partial.
- **Low representation of end-of-life modelling**: Few studies explicitly model processes, such as demolition, material recovery, or recycling, despite their relevance in transport infrastructure.
- **Restricted consideration of indirect/off-site impacts:** Impacts beyond the immediate project boundary such as modal shifts, land take, biodiversity loss in adjacent ecosystems, and cumulative impacts over time or across multiple infrastructure projects.
- **Variability in temporal scope and baseline definition:** Time horizons and baseline assumptions differ substantially between studies, particularly in scenario-based analyses.

These findings suggest a growing need for integrative scoping approaches combining life cycle-based rigour with spatial and policy-oriented perspectives.

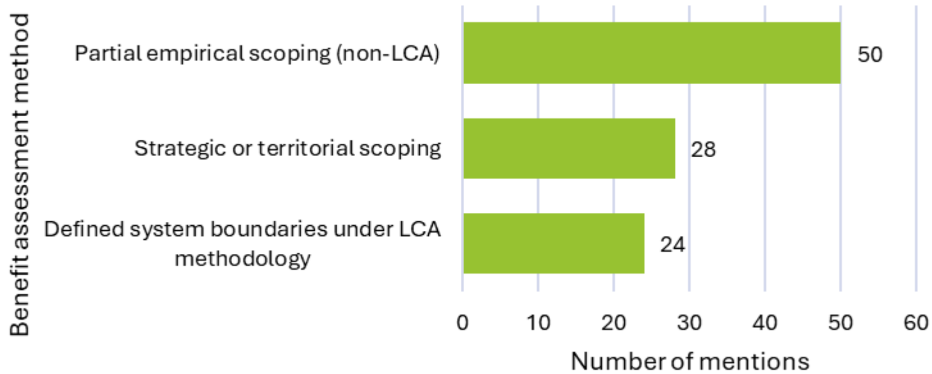

Figure 6: Frequency of scoping approaches used to define system boundaries in case studies, showing the predominance of partial empirical scoping over strategic territorial approaches and fully defined LCA system boundaries.

3.6. INVENTORY DATA

The assessment of inventory data across the reviewed case studies revealed significant variation in terms of depth, transparency, and validation. This variation is closely tied to the nature of the study—whether it is technical, strategic, experimental, or conceptual—and has direct implications for the replicability and policy relevance of the findings. While some cases offer precise, structured datasets aligned with recognized methodologies, others remain largely descriptive or rely on undocumented assumptions and secondary sources.

A clear pattern emerges quantitative field data and spatial analysis tools are the most used data types, while laboratory studies and formal modelling remain less prevalent. The level of detail in inventory data also tends to correlate with the degree of technical specificity and the life cycle phase under evaluation (Figure 7).

1. **Field data collection (51 studies; 50%):** This was the most frequently used inventory source, these studies gathered empirical data through on-site measurements of air, water, soil quality, or biodiversity indicators (e.g., roadkill monitoring, vegetation surveys, monitoring of amphibian road crossings). While not always structured as life cycle inventories, these datasets are often well-documented, statistically processed, and replicable. They provide high spatial and temporal resolution, making them particularly valuable for localized impact assessment and ecological monitoring.

2. **Spatial analysis (44 studies; 43%):** Spatial datasets and GIS tools are central to mapping habitat connectivity, corridor fragmentation, or landscape-scale risk areas. These studies typically define spatial boundaries clearly and use georeferenced layers derived from satellite data, land use maps, or species distribution models. While spatial analysis is not always integrated with life cycle metrics, it contributes critical insights into ecosystem function and the spatial dimension of infrastructure impacts.

3. **Statistical and predictive modelling (35 studies; 34%):** These approaches include simulations, regression models, or multi-criteria decision analyses used to estimate environmental impacts or compare alternative scenarios. While powerful in forecasting and decision support, these studies often rely on assumptions and proxy indicators, requiring strong documentation of methods and sensitivity analyses to ensure credibility.

4. **Stakeholder and qualitative data (23 studies; 23%):** This category includes interviews, perception surveys, participatory mapping, and policy reviews. These studies are often valuable for contextual understanding and governance analysis but rarely provide structured numerical inventories. The transparency of such data depends largely on how well assumptions, sample selection, and coding procedures are documented

5. **Laboratory and experimental data (18 studies; 18%):** Less common, these include controlled tests on material properties, pollutant emissions, or noise attenuation measures. Although technically rigorous, such studies often have limited geographic applicability or lack broader system integration. Nevertheless, they offer highly reliable data for specific parameters, especially in construction and materials analysis.

6. **Other / Mixed sources (23 studies; 23%):** This residual category includes data derived from literature reviews, institutional reports, or undocumented models. While these can be useful for scoping or exploratory analyses, they often suffer from limited traceability and lack standardized metadata.

Across the reviewed case studies, inventory data practices vary in terms of structure, transparency, and level of detail. Studies based on field data collection and spatial analysis generally provide more detailed and well-documented datasets. In contrast, studies relying on qualitative, mixed, or secondary data sources more frequently lack explicit documentation of data sources, assumptions, and processing methods.

Inventory data practices vary considerably across the reviewed studies in terms of structure, transparency, and level of detail. Field data collection and spatial analysis are associated with the most structured and well-documented datasets, while studies relying on qualitative, mixed, or secondary sources less frequently provide explicit documentation of data sources, assumptions, and processing methods. Only a subset of cases integrates multiple data types — such as spatial, ecological, and life cycle-based inventories — within a single assessment framework. This heterogeneity has direct implications for cross-study comparability: without minimum standards for inventory documentation and metadata reporting, it remains difficult to aggregate findings, benchmark tools against one another, or build cumulative knowledge across infrastructure contexts and geographies.

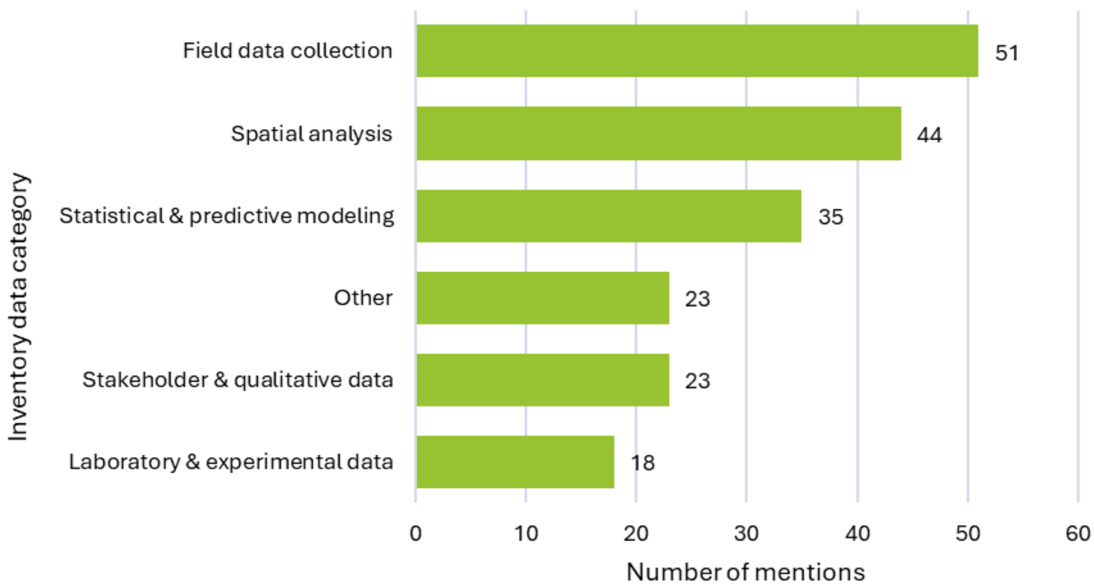

Figure 7: Grouped frequency of inventory data types used in case studies, with field data collection and spatial analysis emerging as the most common sources, followed by predictive modelling and stakeholder-derived qualitative information.

3.7. IMPACT ASSESSMENT METHODS

A diverse set of impact assessment methods is observed across the case studies, ranging from highly standardized, quantifiable approaches to descriptive, spatial, and ecological frameworks. This methodological plurality reflects the varying objectives, scales, and data availability associated with different types of infrastructure assessments. While formal LCA-based methods offer precision and comparability, qualitative and spatial approaches are better suited for capturing complex ecological dynamics, especially in planning and territorial governance contexts.

The coexistence of these paradigms' points to a structural gap in current practice: spatial sensitivity and ecological relevance are rarely combined with reproducible indicators and scenario-based modelling within a single assessment framework. Bridging this methodological divide, integrating direct and indirect impacts while addressing biodiversity comprehensively throughout the infrastructure life cycle, remains one of the central challenges for the development of next-generation assessment tools in the transport sector.

1. **Spatial analysis and GIS-based methods (46 studies; 45%):** The most common type of assessment method (Figure 8), Circuitscape, least-cost path analysis, or mesh fragmentation indices are widely used. These studies often emphasize spatial configuration over numerical precision, and their strength lies in the visualization of ecological risk areas and mitigation opportunities. While not standardized in the LCA sense, they are essential for territorial and conservation planning.

2. **Simulation and predictive modelling (35 studies; 34%):** These methods involve scenario analysis, regression modelling, or probabilistic tools to estimate future impacts. Applications include habitat loss projections, traffic-related emissions, or vegetation growth under different management schemes. These tools help forecast system behaviours under uncertainty, although their transparency and reproducibility depend heavily on the documentation of assumptions and model structure.

3. **Ecological indicators and bioindicators (33 studies; 32%):** This category includes species presence/absence data, diversity indices, or biological metrics derived from bioaccumulation or vegetation health. These methods are particularly useful in the operation and monitoring phases, as they reflect real environmental conditions. However, they often lack direct linkage to impact categories unless complemented by geospatial or emission modelling.

4. **Life Cycle Assessment (LCA) (28 studies; 28%):** These studies represent the most methodologically formalized group. They often use ReCiPe (life cycle impact assessment method combining midpoint and endpoint indicators), IPCC, or CML (midpoint-oriented life cycle impact assessment method) Baseline methods to assess environmental impacts such as GWP (global warming potential), acidification, eutrophication, and resource depletion. Tools like SimaPro, OpenLCA, or GaBi are commonly used. These methods provide high comparability and traceability, particularly in studies addressing construction materials, infrastructure alternatives, or cradle-to-grave evaluations.

5. **Qualitative or narrative assessment (26 studies;26%):** These methods are typically employed in strategic or early-phase planning documents. Impacts are described narratively or organized into matrices (e.g., environmental component vs. infrastructure action), without quantified results. While less rigorous in terms of metrics, these assessments offer valuable insights into perceived risks, governance issues, and potential conflicts.

6. **Unspecified or no formal method (22 studies; 22%):** This category often applies to conceptual documents, exploratory analyses, or policy-driven reports. In these cases, impacts are mentioned or discussed, but no structured approach is followed, limiting traceability and practical applicability.

7. **Stakeholder-based and perception analysis (15 studies; 15%):** Impact assessments were derived from interviews, surveys, or participatory workshops. These methods are valuable for capturing local knowledge, stakeholder concerns, and socio-ecological context. However, the subjectivity and lack of quantification can reduce comparability with technical studies.

8. **Multi-Criteria Decision Analysis (MCDA) (8 studies; 8%):** MCDA frameworks help compare different infrastructure or policy scenarios based on environmental, social, and technical criteria. Though powerful for decision support, they depend heavily on the selection and weighting of criteria, which may introduce subjectivity.
9. **Economic valuation and monetization:** The least applied approach includes cost-benefit analysis, ecosystem service valuation, or willingness-to-pay studies. While monetization helps translate

ecological impacts into policy-relevant terms, its low representation suggests limited integration of economic perspectives in current biodiversity assessments within the transport sector.

Therefore, while impact assessment methods vary widely in complexity and orientation, there is a visible shift toward spatially explicit and predictive tools, particularly when ecological impacts are central. Nonetheless, to ensure decision-making relevance and cross-case comparability, future frameworks must better integrate standardized LCA methods with ecological models and participatory processes.

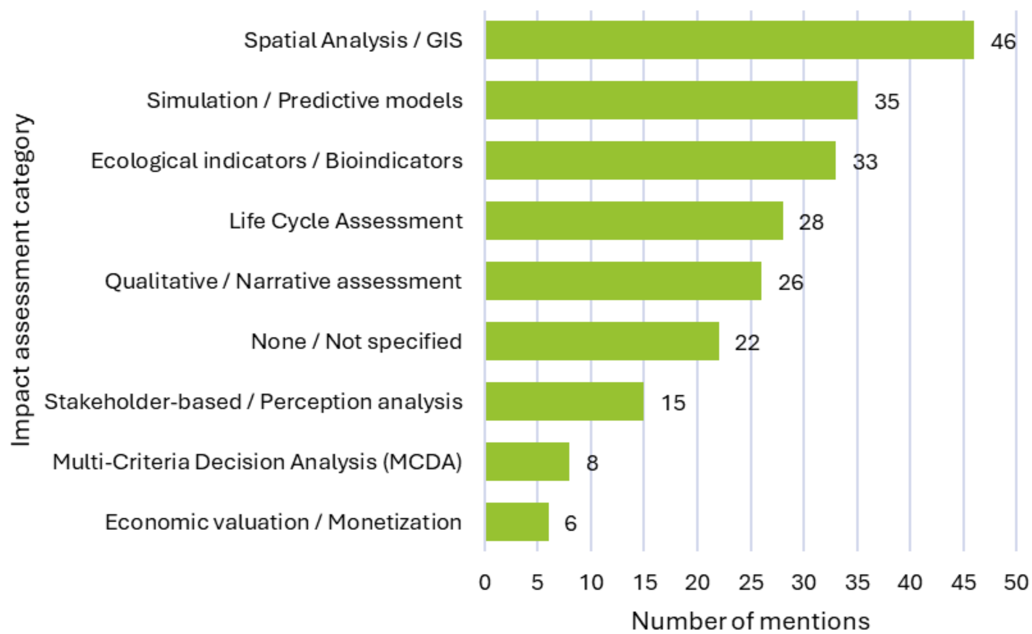

Figure 8: Distribution of impact assessment methods across case studies, revealing the predominance of spatial and predictive approaches, while monetization and decision-support tools such as MCDA remain comparatively underused.

3.8. BENEFIT ASSESSMENT METHODS

The assessment of benefits in studies focused on transport and biodiversity remains an emerging and often underdeveloped dimension. While considerable progress has been made in modelling and quantifying negative environmental impacts, particularly in areas such as habitat fragmentation, species mortality, noise pollution, and greenhouse gas emissions, the systematic identification and valuation of ecological or functional benefits remains limited, inconsistent, and largely qualitative. This asymmetry partly reflects a broader tendency in environmental assessment to frame nature in instrumental terms, measuring what infrastructure takes from ecosystems rather than what interventions can return to them.

Across the 102 reviewed case studies, benefit assessment was found to be rare, fragmented, and highly heterogeneous. Most studies (81 studies, 79%) did not apply a structured framework for identifying or quantifying ecological or functional benefits. These are mostly technically focused studies that model impacts in detail—such as emissions, noise, or structural performance—but do not evaluate ecological or functional gains resulting from the intervention. This highlights a common asymmetry in infrastructure assessment: while impact analysis is methodologically advanced, benefit assessment remains marginal or omitted entirely. Recent initiatives such as the ECOV4R project (UIC, 2026) have begun to address this gap by developing structured, scalable methodologies for ecosystem service assessment in the rail sector, offering a potential reference framework for future benefit assessment practice.

The following categories describe the types of benefit assessment methods observed across the dataset. Some studies applied more than one approach and are therefore represented in multiple categories.

1. **Qualitative or descriptive evaluations of benefits (11 studies; 11%):** These assessments describe benefits narratively, often in relation to improved ecological connectivity, habitat quality, or biodiversity awareness. Typical examples include reports on the effectiveness of wildlife crossings, improved decision-making due to biomonitoring programs, or long-term landscape restoration planning. While these accounts provide important insights, they generally lack quantifiable baselines, do not use structured metrics, and are difficult to compare across contexts.

2. **Scenario comparison and policy options (4 studies; 4%):** This approach assesses potential benefits through comparison of alternative designs, planning options, or policy pathways. Benefits are typically inferred from the relative improvement over a baseline (e.g., reduced fragmentation, enhanced resilience, fewer conflicts). While not always fully quantified, these comparisons offer a functional way to demonstrate the added value of more ecological design or regulation.

3. **Quantitative ecological gains (3 studies; 3%):** Only 3 studies attempted to assess benefits using ecological indicators such as increased habitat area, reduced mortality rates, or species population trends. Although still limited in number, these studies represent a step toward more evidence-based benefit measurement, often tied to empirical monitoring or predictive modelling.

4. **Stakeholder-defined or perception-based benefits (2 studies; 2%):** These assessments rely on surveys or participatory processes to capture perceived improvements in environmental quality or ecosystem services. While highly context-sensitive and useful for community engagement, these methods typically lack objective benchmarks or replicable indicators.

5. **Cost-effectiveness analysis (2 studies; 2%):** Used in only 1 study, this method estimates the relative cost of achieving specific ecological outcomes, offering a useful but rare lens for comparing mitigation options. However, it was not accompanied by formal monetization or integration into full life cycle costing frameworks.

6. **Economic valuation / monetization (0 studies; 0%):** Not present in any of the reviewed cases (0 studies), this highlights a major gap in current practice. Despite growing interest in ecosystem service valuation and green infrastructure finance, no study included in the review applied formal economic valuation tools such as willingness-to-pay, avoided damage costs, or ecosystem service monetization.

Baseline criteria, when used, were generally implicit or inconsistently defined. Some studies compared alternative project scenarios, while others relied on current land-use configurations or assumed "business-as-usual" conditions. Very few defined a baseline in technical, temporal, or regulatory terms, and almost none applied structured comparative frameworks. This lack of consistency undermines the interpretability of results and limits their applicability in planning and policy. The ECOV4R framework (UIC, 2026) offers a relevant precedent, establishing a structured five-step process that explicitly defines baseline conditions as a counterfactual scenario against which intervention impacts are measured.

Hence, benefit assessment remains one of the least developed areas in biodiversity-integrated infrastructure studies. Future frameworks should aim to formalize benefit definitions, propose standardized indicators, and encourage greater integration with LCA, ecosystem service models, and stakeholder feedback tools.

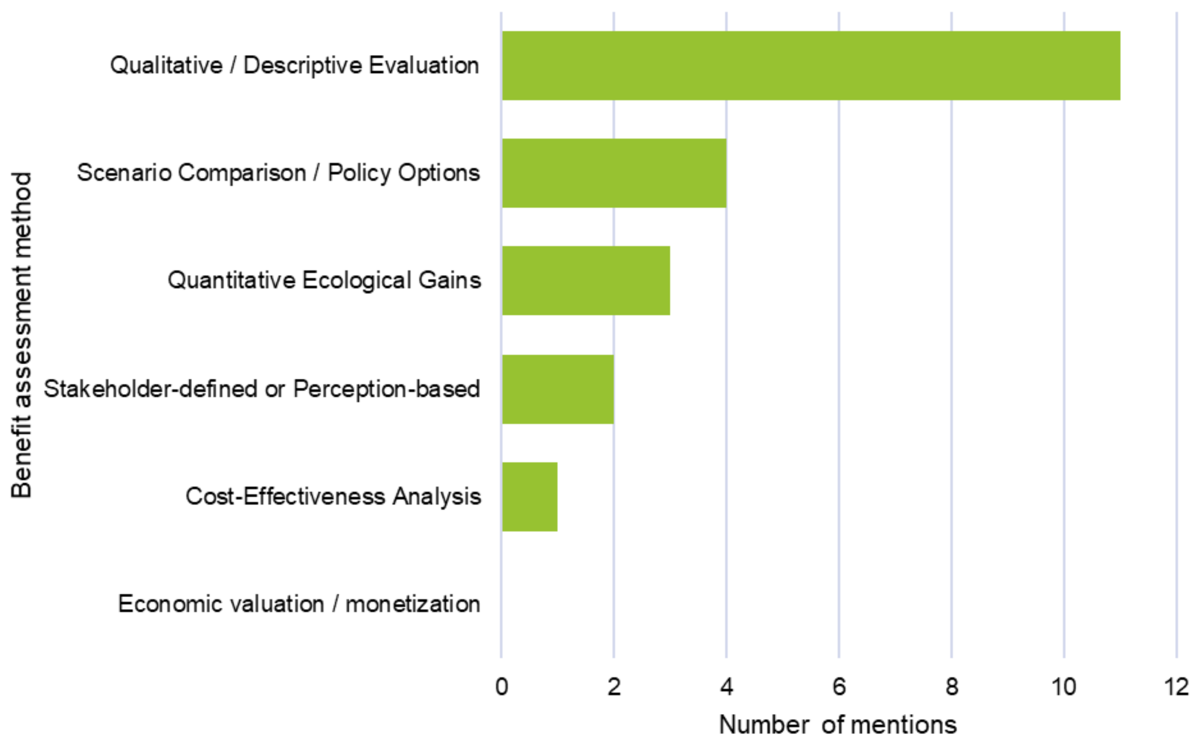

Figure 9: Frequency of benefit assessment methods in reviewed case studies, showing a strong reliance on qualitative evaluations and scenario comparisons, with limited use of cost-effectiveness and economic valuation approaches.

3.9. EXPERT ASSESSMENT OF BARRIERS

The structured expert consultation complements the bibliometric evidence of Sections 3.1–3.9 by surfacing the institutional, fiscal, and governance realities that shape how — and whether — available tools are effectively deployed in operational contexts. While the literature review characterises the methodological state of the art, the Delphi study situates it within the organisational environment that determines whether tools reach practice. The findings below are organised by level of expert agreement and connected directly to the patterns identified in the preceding sections (Figure 9).

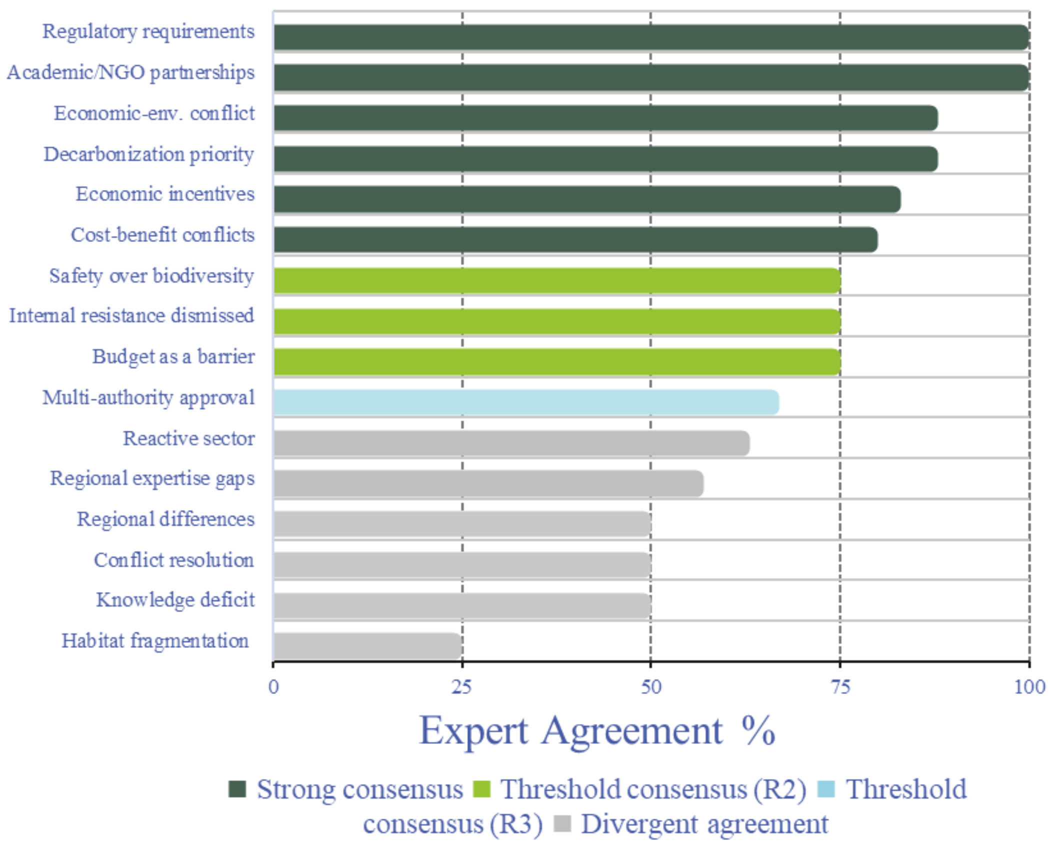

Figure 10: Expert agreement on barriers to biodiversity integra in railway infrastructure projects (% respondents aligned with dominant response). Color coding: strong consensus (≥83%), R2 threshold (75%), R3 threshold (67%), sub-threshold (<67%).

1. **Regulatory Drivers and the Compliance Ceiling** Unanimous consensus emerged that regulatory requirements constitute the primary driver of biodiversity prioritization in European railway organizations (100%, R2). All panel members identified core EU-level frameworks (Birds and Habitats Directive, Environmental Impact Assessment legislation, and emerging Corporate Sustainability Reporting Directive (CSRD) requirements, etc.) as the baseline reference for biodiversity action. This result is consistent with the literature review's finding that planning-phase assessments are predominantly driven by regulatory mandates, and that tool development tends to follow legislative stimulus rather than proactive organizational strategy. What gives this finding analytical weight, however, is its interaction with a critical Round 3 result: when asked how biodiversity integration could be accelerated beyond current levels, 83% of experts pointed to economic incentives aligned with environmental performance, not to stronger or more prescriptive regulation. This suggests that practitioners perceive the existing regulatory framework as having approached its effective limit as a

lever for behavioural change. Regulation is seen as necessary but not sufficient: it sets the floor, but the resources it demands for compliance constrain the capacity to go beyond it.

2. **Operational Hierarchies and Fiscal Constraints.** The panel identified safety and social requirements as consistently superseding biodiversity concerns in operational decision-making (83%, R2). This safety primacy reflects an entrenched institutional hierarchy that is unlikely to shift through normative pressure alone. It helps explain a pattern observed in the literature review: maintenance and end-of-life phases, where operational trade-offs are most acute, are the most underrepresented in current assessment practice (Section 3.3).

- **Budget limitations** were identified as the second most significant operational constraint (75%, R2), and Round 3 confirmed that financial resource scarcity after regulatory compliance is the primary reason organizations do not implement biodiversity measures beyond mandatory requirements (67%, R3). This fiscal dynamic is structural, not motivational: 75% of the panel explicitly rejected the notion that voluntary initiatives have minimal biodiversity impact, indicating that organizational conviction is not the primary binding constraint; available resources are.

- **Stakeholder Conflicts and the Knowledge–Willingness Debate.** The Delphi study revealed that economic-environmental tensions constitute the dominant stakeholder conflict in biodiversity integration processes (88%, R2), and that conflicts between costs and environmental benefit require the longest resolution time of any conflict type (80%, R3). Multi-authority approval processes were identified as the dominant structural barrier preventing proactive rather than reactive biodiversity integration (67%, R3). These findings are consistent with the literature review's observation that only 8% of reviewed studies were classified as corporate frameworks, institutionalized, replicable approaches to ecological governance, while the majority addressed specific technical solutions without broader systemic integration. Particularly notable is the unresolved tension between knowledge deficits and organizational willingness as the primary obstacle to biodiversity integration. Even under the hypothetical scenario of unlimited resources, the panel remained divided: 50% identified an unclear business case for proactive measures as the main obstacle, while 33% attributed it to a lack of specialized technical knowledge. This split persisted across all three rounds without reaching consensus.

- **Regional Disparities in Implementation.** Substantial agreement emerged on the significance of regional implementation disparities across European member states. Environmental awareness gaps (86%, R2) and financial resource differences (83%, R2) were both strongly endorsed as explanatory factors. However, no consensus emerged on which of these factors carries greater explanatory weight: economic capacity attracted plurality support (50%, R3) but fell below the threshold, followed by cultural attitudes toward environmental responsibility (33%, R3). This partial alignment suggests that both factors operate simultaneously, but with different relative weights depending on national context. The geographic distribution of the literature review reinforces this conclusion: European studies dominate the sample (49 out of 102), yet within Europe there is significant variation in regulatory capacity, institutional maturity, and funding availability, particularly between Western and Central-Eastern European contexts.

Overall, the Delphi findings reveal a sector operating under structural constraints that no single methodological framework can resolve in isolation. The compliance ceiling, fiscal hierarchies, stakeholder conflicts, and regional disparities identified by experts are not incidental — they are systemic features of the environment in which biodiversity assessment tools must operate. Effective frameworks must therefore be designed with this institutional heterogeneity in mind, offering differentiated pathways rather than a single implementation model.

4. CONCLUSIONS AND RECOMMENDATIONS

The comprehensive review of 102 case studies on biodiversity and transport infrastructure and multi-round expert assessment reveals a rich diversity of methodological approaches, analytical scopes, and implementation strategies. This diversity reflects both the maturity of certain practices—such as impact quantification or construction-phase assessments—and the ongoing need for integration, harmonization, and innovation in others. The following conclusions and recommendations are offered to guide the development and successful implementation of the SYMBIOSIS project.

- **Nature of the activity: Encourage hybrid and actionable frameworks**

The majority of cases are oriented toward specific solutions and strategic planning tools, with fewer focused on services or institutional frameworks. This underscores the opportunity for SYMBIOSIS to position itself as a hybrid initiative that bridges practical application with strategic alignment. The project should:

- Prioritize tools that are both operationally relevant and adaptable to governance frameworks.
- Promote methodologies that combine spatial, regulatory, and technical components.
- Support the development of standards for services (e.g., monitoring, data provision) that are easily replicable and scalable.

- **Life Cycle phases: Move beyond construction and operation**

While operation and construction are the most represented life cycle phases, early planning, maintenance, and renewal/end-of-life remain underdeveloped. A more comprehensive, life cycle-oriented approach is needed across the sector. Assessment practitioners and infrastructure developers should:

  - Integrate modules for maintenance, retrofitting, and end-of-life assessment into existing frameworks.
  - Develop tools that support "design for biodiversity" from the earliest phases of project conception.
  - Encourage cradle-to-grave logic even in cases where full LCA may not be applied.

- **Goal definition: Target multiple audiences with tailored outputs**

The studies analysed reflect a primary focus on researchers, infrastructure developers, and transport agencies, with fewer targeting local communities or conservation NGOs. For assessment tools to achieve meaningful adoption, developers and commissioners of environmental assessment frameworks should:

- Deliver differentiated outputs for each audience type (technical dashboards, policy briefs, participatory maps).
- Foster usability across institutional levels — from local stakeholders to EU-level authorities.
- Support co-creation processes to align technical goals with community values and governance priorities.

- **Scoping: Standardise while allowing for strategic flexibility**

LCA-based scoping remains a minority practice, while partial empirical approaches and strategic or territorial definitions predominate. To address this fragmentation, infrastructure managers, planners, and assessment practitioners should:

- Adopt modular scoping structures that accommodate both technical and strategic boundaries.
- Apply minimum criteria for scoping transparency across all types of activities.
- Integrate spatial planning tools with life cycle-based flows and impacts wherever feasible.

- **Inventory data: Improve transparency and quality control**

Inventory quality varies widely, with a majority of studies relying on empirical or qualitative data and limited fully quantitative inventories. Common gaps include undocumented assumptions, lack of functional units, and inconsistent baseline definitions. To ensure credibility and comparability, practitioners and data providers should:

- Adopt open-source, quality-assured inventory templates where available.
- Apply metadata standards and validation checklists to ensure traceability and replicability.

Integrate data from both formal LCA databases and field-based sources to strengthen inventory robustness.

- **Impact assessment methods: Integrate quantitative and ecological approaches**

Although GIS/spatial analysis and predictive models are widely used, only a minority of studies apply standardised impact methods such as IPCC or ReCiPe. There is a persistent split between technical LCA and ecological spatial logic that limits cross-study comparability. To bridge this divide, assessment practitioners and methodological standard-setters should:

- Develop hybrid assessment protocols that integrate spatial ecological metrics with recognised environmental impact categories.
- Encourage harmonised use of indicators (e.g., GWP, ecosystem connectivity, fragmentation) across methods and infrastructure types.
- Foster transparency in assumptions, weighting criteria, and uncertainty handling as a baseline requirement for any assessment framework.

- **Benefit assessment: Define clear baselines and highlight co-benefits**

Most studies do not evaluate benefits systematically, with a significant proportion not addressing benefits at all. When benefit assessment is attempted, it tends to be qualitative or scenario-based. To advance this underdeveloped dimension, infrastructure managers, policymakers, and assessment practitioners should:

  - Promote structured benefit estimation linked to avoided impacts, ecological restoration, and policy compliance.
  - Establish clear baseline conditions — technical, regulatory, and temporal — as a prerequisite for benefit quantification.
- Incorporate metrics for ecosystem services, GHG reductions, and biodiversity gains into comparative analyses, and explore the use of economic valuation methods, such as cost-effectiveness analysis or monetisation of ecosystem services, to enhance the relevance and usability of benefit assessments in policy and investment contexts.

The findings presented in Section 3 converge on a single structural insight: effective tools for biodiversity integration must be designed around the institutional and fiscal realities of the organisations expected to use them, not around methodological ideals alone. This conclusion emerges from both the bibliometric evidence and the expert consultation and has direct implications for how assessment frameworks, and particularly their inventory components, are developed and deployed in practice.

Three concrete requirements emerge from this dual analysis. First, benefit assessment frameworks and ecological gain quantification tools must produce outputs framed in economic and business logic, cost savings, avoided liability, performance-linked reporting, if they are to overcome the compliance ceiling identified by Delphi experts as the dominant constraint on voluntary action. As long as the prevailing institutional logic remains compliance-driven, methodologically sound tools that cannot demonstrate a return on investment will remain underused, regardless of their technical quality. Second, assessment modules for maintenance, renewal, and end-of-life phases must be lightweight and proportionate to organisational capacity. The Delphi study confirmed that financial resource scarcity after regulatory compliance is the primary reason organisations do not go beyond mandatory requirements, meaning that tools perceived as additional data collection burdens will be systematically deprioritised in precisely the phases where assessment coverage is already weakest. Third, assessment tools must be modular and contextually adaptable. The unresolved expert divergence on whether the primary barrier to biodiversity integration is an unclear business case or a lack of technical knowledge signals that a single harmonised standard will produce uneven results across the sector. Organisations in different institutional, regulatory, and financial contexts require differentiated pathways: structured methodological guidance for technically underequipped organisations, and economic framing outputs for those whose primary constraint is an unclear return on biodiversity investment.

Taken together, these requirements point toward a new generation of assessment tools that are not only methodologically rigorous but institutionally legible, designed to function within the governance hierarchies, fiscal constraints, and regional disparities that the evidence in this deliverable has documented.

5. INTERPRETING THE EVIDENCE THROUGH EXPERT INSIGHT

The results presented in Section 3 document what current practice looks like — the tools in use, the phases assessed, the methods applied, and the gaps that persist. This section draws on the expert consultation to ask a different question: why do these patterns exist, and what do they reveal about the conditions under which biodiversity integration actually occurs in practice?

Four interpretive insights emerge from the convergence of bibliometric evidence and expert consensus.

The compliance ceiling. The virtual absence of benefit assessment in the reviewed studies is consistent with a sector that allocates its environmental resources to meeting minimum legal requirements rather than to demonstrating or quantifying ecological gains. As long as the dominant institutional logic is compliance-driven, voluntary investment in structured benefit quantification remains a low priority, regardless of methodological availability.

Fiscal hierarchies and phase coverage. The systematic underrepresentation of end-of-life assessments and the predominance of construction and operation-phase studies reflects a predictable institutional logic: organisations prioritise phases where regulatory obligations are clearest and safety requirements most visible. Phases perceived as less immediately regulated — maintenance scheduling, infrastructure retrofitting, decommissioning — receive less structured assessment attention as a direct consequence of resource scarcity after compliance.

A dual constraint on tool adoption. The prevalence of partial empirical scoping and the coexistence of diverse, non-standardised impact assessment methods may reflect a heterogeneous barrier landscape: in some organisations, tools are available but the business rationale for applying them is absent; in others, the will may exist, but the methodological capacity does not. A single harmonised framework cannot resolve both constraints simultaneously unless it is explicitly designed with this heterogeneity in mind.

Regional disparities and the limits of uniform policy. The absence of expert consensus on the primary driver of regional implementation disparities signals that uniform policy instruments, whether regulatory or financial, will produce uneven results across member states. Organisations in countries with high environmental awareness but limited funding face fundamentally different constraints than those in countries with available resources but weaker governance traditions. Effective frameworks must therefore offer differentiated pathways rather than a single implementation model.

6. IMPLICATIONS FOR WP3 AND CONNECTION WITH OTHER WORCK PACKAGES

The findings of this deliverable, drawn from both the systematic literature review and the structured expert consultation, provide the analytical foundation upon which the remaining tasks of Work Package 3 will build. This section outlines how the evidence gathered in D3.1 informs the next steps within WP3 and identifies the connections with other work packages in the SYMBIOSIS project.

Informing Task 3.2: Climate Resilience Mapping. The review identified significant gaps in the integration of climate-related life cycle phases, particularly maintenance and end-of-life, into current biodiversity assessment practice. The geographic and spatial analysis methods documented in Section 3.7, including GIS-based habitat connectivity modelling and landscape fragmentation indices, provide a direct methodological reference for the development of railway climate risk maps at European and regional scale. The expert consultation further reinforced that operational phases where climate hazards are most acute, flooding, fire, landslides, are precisely those where structured assessment frameworks are weakest, underscoring the need for the synergic approach to resilience and biodiversity that Task 3.2 pursues.

Informing Task 3.3: Blue and Green Infrastructure Guidance. The characterisation of benefit assessment methods in Section 3.9 revealed that ecological gain quantification remains the least developed dimension in current practice, with no reviewed study applying formal economic valuation. This gap directly motivates the multi-stakeholder approach of Task 3.3, which seeks to define variables and their relative importance in the design and management of railway ecological assets. The catalogue of Nature-based Solutions to be developed in Task 3.3 can draw on the typology of specific solutions identified in Section 3.2, while addressing the baseline definition and co-benefit quantification gaps documented across the review.

Informing Task 3.4: Biodiversity-CO2 Calculator. The inventory data analysis in Section 3.6 documented wide variation in data depth, transparency, and validation across the reviewed studies, with only a subset integrating spatial, ecological, and life cycle-based inventories within a single framework. This heterogeneity directly informs the design requirements for the Biodiversity-CO2 Calculator to be developed in Task 3.4, which must be both methodologically robust and proportionate to the organisational capacity constraints identified by Delphi experts. The compliance ceiling and fiscal hierarchy findings of Section 3.9 are particularly relevant here: a calculator that cannot generate outputs legible in business and regulatory terms is unlikely to achieve adoption beyond the organisations already committed to voluntary action.

Connections with WP4 and WP5. Beyond WP3, the findings of this deliverable have direct relevance for the monitoring and data collection systems to be developed in WP4. The inventory data gaps documented in Section 3.6, particularly the lack of standardised metadata and the limited integration of remote sensing with field-based data, provide concrete evidence base for defining the data requirements and monitoring indicators that WP4 will need to address. At the policy level, the regulatory analysis emerging from the expert consultation, particularly the identification of the CSRD, the EU Nature Restoration Law, and EIA legislation as the primary drivers of biodiversity action, feeds directly into the cross-cutting policy recommendations and guidelines to be developed in WP5, informing both the adaptation of the Corporate Sustainability Reporting Directive and the design of public procurement criteria with biodiversity metrics.

Looking ahead. Taken together, the evidence in this deliverable suggests that the most impactful contributions of WP3 will be those that simultaneously address methodological gaps and institutional barriers, developing tools that are technically rigorous, modular in design, economically legible, and calibrated to the heterogeneous regulatory and fiscal contexts of European railway operators. D3.1 has mapped the landscape; the remaining deliverables of WP3 will build within it.

ANNEX I

Task 3.1.1: Explore and characterize existing operational tools for assessing environmental impacts and benefits

Assess the current experience experiences (case studies) of environmental impact assessment in linear infrastructures published in 2021, 2022, 2023, 2024 according to:

- Nature of the activity (service, corporate, specific solution, plan)
- Life cycle phases (design, construction, maintenance, operation and renewal of infrastructure)
- Goal definition (target audience)
- Scoping (definition of system boundaries)
- Inventory data (level of transparency and quality assessment)
- Impact assessment methods (e.g. IPCC, Environmental Footprint, Natural Capital, Monetization...)
- Benefit assessment methods (Baseline criteria)

CASE STUDY NO.1

Name:	*Road effects on benthic macroinvertebrate assemblages in boreal headwater streams*
Country:	Norway (2022)
Assessed activity:	Impact of road crossings on benthic macroinvertebrate communities in small temperate headwater streams
Nature of the activity:	Transport
Life cycle phases:	Operation and maintenance of road infrastructure
Goal definition:	Evaluating how road crossings influence the structure and function of benthic macroinvertebrate assemblages in headwater streams
Target audience:	Scientists, policymakers, environmental managers, road planners
Scoping:	Investigates the ecological impact of roads on small streams, focusing on fragmentation, hydrological changes, sedimentation, and pollution
Nature of inventory data:	Field data collection from 12 small streams in southeastern Norway, comparing macroinvertebrate assemblages in road-impacted and control streams
Quality assessment:	Statistical analyses, including nested ANOVA and multivariate methods (MDS, SIMPER), to assess species composition, abundance, and functional feeding groups
Impact assessment:	• Analysis of macroinvertebrate density and species richness • Evaluation of species composition and functional feeding groups (e.g., predators, grazers, shredders) • Assessment of pollution effects (e.g., increased chloride levels due to road salting) • Consideration of fragmentation impacts on ecological continuity
Environmental impact categories:	• Biodiversity loss in freshwater ecosystems • Altered species composition and functional feeding groups • Pollution effects from road salting and runoff • Habitat fragmentation and its effects on ecological continuity
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.2

Name:	*Linear infrastructure and associated wildlife accidents create an ecological trap for an apex predator and scavenger*
Country:	Sweden (2024)
Assessed activity:	Impact of linear infrastructure (roads, railways, powerlines) on Golden Eagle (*Aquila chrysaetos*) populations
Nature of the activity:	Transport
Life cycle phases:	Operation and maintenance of linear infrastructure
Goal definition:	Investigating whether roads, railways, and powerlines create an ecological trap for Golden Eagles by providing feeding opportunities from wildlife roadkill while increasing mortality risk
Target audience:	Scientists, conservationists, policymakers, environmental agencies
Scoping:	Examines the spatial and demographic consequences of eagle dependence on carcasses from wildlife traffic accidents and electrocution risks near powerlines
Nature of inventory data:	• GPS tracking data from 74 Golden Eagles over 11 years (2010–2020) • Wildlife traffic accident statistics (2010–2023) • Eagle mortality data from national databases
Quality assessment:	• Statistical modeling (step selection functions, Cox proportional hazards model) • Comparative survival analysis across different habitat types • Multiannual dataset with standardized GPS tracking methods
Impact assessment:	• Habitat selection analysis based on movement tracking • Survival analysis comparing eagle mortality in different habitats • Ecological trap assessment using demographic data and habitat selection patterns
Environmental impact categories:	• Wildlife mortality due to traffic collisions and electrocution • Habitat selection shifts leading to increased mortality risk • Potential population decline of Golden Eagles due to maladaptive habitat selection
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.3

Name:	*Urban runoff mortality syndrome in zooplankton caused by tire wear particles*
Country:	China (2023)
Assessed activity:	Impact of tire wear particles (TWP) from urban roadway runoff on zooplankton populations
Nature of the activity:	Transport
Life cycle phases:	Operation and maintenance of road infrastructure
Goal definition:	Investigating the acute and chronic toxicity of urban stormwater runoff containing TWP and tire-derived chemicals on zooplankton populations
Target audience:	Scientists, environmental regulators, urban planners, policymakers
Scoping:	Evaluates the toxicity of TWP and specific chemical components on freshwater zooplankton populations
Nature of inventory data:	• Laboratory experiments exposing zooplankton (Daphnia pulex) to stormwater runoff and TWP leachates • Comparative toxicity testing on 11 zooplankton species • Analysis of survival, reproduction, and population dynamics under exposure to contaminants
Quality assessment:	• Statistical analysis of survival rates, reproductive success, and life history traits • Controlled experimental design with multiple replicates • Identification of key toxicants through chemical assays
Impact assessment:	• Acute and chronic toxicity bioassays on zooplankton • Life table experiments measuring population growth, survival rates, and reproductive output • Comparative sensitivity analysis among zooplankton species
Environmental impact categories:	• Water contamination from tire wear particles and associated chemicals • Toxicity-induced declines in zooplankton populations • Ecosystem disruptions due to cascading effects on aquatic food webs
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.4

Name:	*Roads reduce amphibian abundance in ponds across a fragmented landscape*
Country:	Hungary (2021)
Assessed activity:	Impact of roads and railways on amphibian abundance in ponds within a fragmented landscape
Nature of the activity:	Transport
Life cycle phases:	Operation and maintenance of road and railway infrastructure
Goal definition:	Assessing the relationship between amphibian abundance and proximity to roads/railways to determine the extent of road-effect zones and inform conservation strategies
Target audience:	Scientists, conservationists, policymakers, environmental agencies
Scoping:	Investigates how road infrastructure affects amphibian populations by analyzing habitat accessibility, road density, and species abundance in freshwater ponds
Nature of inventory data:	• Field surveys conducted at 30 freshwater ponds in a peri-urban/agricultural landscape • Measurement of landscape variables within a 1000-m radius around ponds • Analysis of larval amphibian abundance in relation to road proximity and habitat fragmentation
Quality assessment:	• Use of multi-species abundance models (MSAM) and N-mixture models for statistical analysis • Application of Bayesian inference for species-level responses • Consideration of habitat quality and pond characteristics
Impact assessment:	• Analysis of the road-effect zone extending up to 1 km from highways • Comparison of accessible vs. total habitat as predictors of amphibian abundance • Assessment of species-specific responses to road and habitat fragmentation
Environmental impact categories:	• Habitat fragmentation due to road networks • Reduction in amphibian abundance near highways • Negative effects on species dispersal and breeding site connectivity • Potential road-induced mortality and pollution effects on aquatic ecosystems
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.5

Name:	*BIM-based environmental impact assessment for infrastructure design projects*
Country:	Netherlands (2021)
Assessed activity:	Integration of Building Information Modeling (BIM) with Environmental Impact Assessment (EIA) for infrastructure projects
Nature of the activity:	Infrastructure operation
Life cycle phases:	Design, construction, operation, and maintenance of infrastructure
Goal definition:	Developing a continuous, automated BIM-based framework to integrate EIA into infrastructure design, allowing for real-time environmental impact assessment during decision-making
Target audience:	Infrastructure designers, engineers, sustainability experts, policymakers
Scoping:	Focuses on integrating Life Cycle Assessment (LCA) with BIM to streamline the environmental impact assessment process and improve sustainability considerations in infrastructure design
Nature of inventory data:	• BIM data from infrastructure projects • Environmental impact databases (e.g., Dutch National Environmental Database) • Material-specific life cycle impact factors
Quality assessment:	• Validation through a case study in Utrecht, Netherlands • Comparison with traditional EIA processes to measure accuracy and efficiency • Expert evaluation via a workshop with designers and sustainability professionals
Impact assessment:	• Life Cycle Assessment (LCA) based on ISO 14040 standards • Environmental Impact Score (EIS) calculations integrated with BIM • Bidirectional data exchange between BIM models and EIA databases • Visualization of environmental impact in the BIM design environment
Environmental impact categories:	• CO_2 emissions, energy consumption, and raw material use • Waste generation and environmental degradation from infrastructure projects • Sustainability performance of construction materials and methods
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.6

Name:	*Life-cycle modelling of concrete cracking and reinforcement corrosion in concrete bridges*
Country:	China (2021)
Assessed activity:	Long-term performance assessment of reinforced concrete (RC) bridges subject to cracking and steel reinforcement corrosion
Nature of the activity:	Transport infrastructure – highway bridge
Life cycle phases:	Operation, maintenance, and renewal
Goal definition:	To model and quantify the impact of concrete cracking on reinforcement corrosion and service life of RC bridges under varying maintenance cycles
Target audience:	Bridge managers, civil engineers, infrastructure maintenance planners, policymakers
Scoping:	Focuses on deterioration processes in RC highway bridges, particularly corrosion induced by crack propagation. Evaluates intervention strategies under different environmental and maintenance conditions (normal vs. coastal environments)
Nature of inventory data:	Empirical inspection data of crack widths from an operational highway bridge (Long Feng Xi Bridge), collected over 8 years on three specific cracks
Quality assessment:	Models calibrated using real inspection data; analysis performed using auto-regressive modelling, Fick's law for chloride diffusion, and probabilistic reliability methods (FOSM). Limitations noted regarding exclusion of traffic loads and real-time environmental variability
Impact assessment:	• Crack propagation prediction using auto-regressive modelling • Chloride diffusion and steel corrosion rate estimation based on Fick's second law and empirical models • Reliability index (β) estimation for concrete cracking and rebar cross-section loss • Probability of failure (PoF) computed for both cracking and corrosion thresholds
Environmental impact categories:	• Structural integrity reduction due to environmental degradation (e.g., chloride ingress, cracking) • Accelerated corrosion in coastal environments • Reduced service life of infrastructure due to environmental exposure
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.7

Name:	*Road crossings hinder the movement of a small non-migratory stream fish*
Country:	Brazil (2023)
Assessed activity:	Impact of road-stream crossings (culverts) on the movement of a small benthic fish (*Rineloricaria aequalicuspis*)
Nature of the activity:	Transport
Life cycle phases:	Operation and maintenance of road infrastructure
Goal definition:	Evaluating the effect of culverts on fish movement probability and identifying environmental factors influencing passage success
Target audience:	Scientists, conservationists, environmental managers, infrastructure planners
Scoping:	• Investigates how culverts impact fish movement and connectivity in freshwater ecosystems • Identifies environmental variables that influence fish passage success (water depth, velocity, perch height)
Nature of inventory data:	• Field data from capture-recapture surveys conducted in a stream section with a road crossing and adjacent free-flowing stream sections • Environmental variables (water depth, velocity, temperature, substrate size) measured over 17 months • Statistical modeling of fish movement probability and influencing factors
Quality assessment:	• Use of multi-state open population models to estimate movement probabilities • Statistical validation of environmental variables influencing movement through the culvert • Comparison of movement probabilities within free stream sections vs. culvert-affected sections
Impact assessment:	• Capture-recapture study to analyze fish movement and culvert passability • Statistical modeling of environmental influences on movement probability • Analysis of habitat fragmentation caused by road infrastructure
Environmental impact categories:	• Reduced fish mobility and habitat connectivity due to culverts • Altered stream hydrology affecting fish movement • Potential long-term population impacts due to restricted movement and genetic isolation
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.8

Name:	*Development and application of a life cycle energy consumption and CO_2 emissions analysis model for high-speed railway transport in China*
Country:	China (2021)
Assessed activity:	Life cycle assessment of energy consumption and greenhouse gas emissions for high-speed rail (HSR) transport using the Beijing–Shanghai HSR as a case study
Nature of the activity:	Transport infrastructure
Life cycle phases:	Design, construction, operation, maintenance, and renewal (partial decommissioning excluded)
Goal definition:	To develop a full life-cycle model (Tsinghua-LCA based) for evaluating energy use and GHG emissions from HSR and to compare its environmental performance with other transport modes
Target audience:	Transport planners, energy policy makers, infrastructure managers, environmental researchers
Scoping:	Assessment includes infrastructure development, train manufacturing and use, and station operations. Emphasizes electricity generation mix and train occupancy rate as key variables influencing environmental impact
Nature of inventory data:	Empirical and modeled data for infrastructure, rolling stock, and operation (2015–2020), using national statistics, technical specifications (e.g., CRH380B trains), and prior LCA studies. Excludes dismantling/scrapping due to minor expected contribution (<0.1%)
Quality assessment:	Based on Tsinghua-LCA Model (TLCAM); transparent assumptions and sensitivity analyses on materials (e.g., cement, steel), power sources, and train occupancy; however, lacks real-time monitoring data for operational emissions
Impact assessment:	• Life Cycle Assessment (LCA) covering three subsystems: infrastructure, rolling stock, and operation • Key indicators: fossil energy use (MJ) and GHG emissions (kg CO_2e) per passenger-km • Use of China-specific energy/emission intensity databases (CLCD, Ecoinvent) • Sensitivity analysis on electricity mix and train occupancy
Environmental impact categories:	• Fossil energy use (MJ/passenger-km) • Greenhouse gas emissions (CO_2e/passenger-km) • Indirect emissions from material production (cement, steel) • Impact of electricity source (coal vs. clean grid)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.9

Name:	*Life cycle assessment of a low-height noise barrier for railway traffic noise*
Country:	Finland (2021)
Assessed activity:	Environmental assessment of different material compositions and construction methods for a 20 m low-height railway noise barrier (LHNB)
Nature of the activity:	Transport infrastructure – railway noise abatement
Life cycle phases:	Design, material production, construction (precast and additive manufacturing), operation (service life), and end-of-life (demolition and landfill)
Goal definition:	To compare the environmental impacts of Portland cement concrete (PCC) and geopolymer composite LHNB designs, including additive manufacturing variants, using life cycle assessment (LCA) methodology
Target audience:	Environmental planners, railway infrastructure designers, policymakers, sustainability researchers
Scoping:	Cradle-to-grave LCA including raw material extraction, production, construction, use (with carbonation), and end-of-life. Functional unit defined as a 20 m LHNB with 10 dB sound absorption
Nature of inventory data:	Combination of primary data (material processing, mix designs, additive manufacturing) and secondary data (GaBi and Ecoinvent databases); includes material transport, energy use, emissions, and carbonation
Quality assessment:	Pedigree matrix applied to assess five quality dimensions (reliability, completeness, temporal, geographical, technological correlation); includes sensitivity analysis on service life and compressive strength normalization
Impact assessment:	• Method: Life Cycle Assessment (LCA) according to ISO 14040 and ISO 14044 standards • Software: GaBi 9.2.0.58 • Impact method: ReCiPe 2016 v1.1 Midpoint (H) • Use of compressive strength– and service life–normalized indicators (Indicator1 and Indicator2) to improve comparability of results across designs
Environmental impact categories:	• Global Warming Potential (GWP) • Fossil Depletion (ADP_FF) • Photochemical Ozone Creation Potential (POCP) • Acidification Potential (AP) • Source-specific emissions from cement, alkali activators, metakaolin, and transport • Carbonation uptake for cement-containing scenarios (S0 and S3)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.10

Name:	*Assessing the ecological impacts of transportation infrastructure development: A reconnaissance study of the Standard Gauge Railway in Kenya*
Country:	Kenya (2021)
Assessed activity:	Ecological impacts of the Standard Gauge Railway (SGR) in Kenya
Nature of the activity:	Transport
Life cycle phases:	Construction, operation, and maintenance of railway infrastructure
Goal definition:	Evaluating stakeholder perceptions of the ecological impacts of the SGR on ecosystems and biodiversity in Kenya
Target audience:	Scientists, policymakers, conservationists, infrastructure planners
Scoping:	• Focuses on the impact of railway infrastructure on ecosystem degradation, fragmentation, and destruction • Assesses direct and indirect environmental consequences of railway development in ecologically sensitive areas
Nature of inventory data:	• Qualitative data from 54 key informant interviews across 14 sites along the SGR corridor • Spatial analysis of environmental impacts using GIS mapping • Thematic content analysis of stakeholder perceptions
Quality assessment:	• Stakeholder-based assessment capturing local knowledge and expert opinions • Triangulation with environmental impact reports and field observations • Use of qualitative data analysis software for systematic coding
Impact assessment:	• Thematic analysis of stakeholder perspectives on ecosystem degradation, fragmentation, and destruction • GIS-based spatial analysis to identify impact hotspots • Comparison of environmental changes before and after SGR construction
Environmental impact categories:	• Habitat fragmentation due to railway barriers • Wildlife movement disruptions and human-wildlife conflicts • Soil and water contamination from construction runoff • Noise pollution affecting surrounding communities and ecosystems • Increased spread of invasive species along railway corridors
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.11

Name:	*Environmental life cycle impact assessment of transportation infrastructure: A multi-case study in international perspective*
Country:	China, Pakistan, Bosnia (2021)
Assessed activity:	Environmental impact assessment of five road infrastructure projects using a unified life cycle analysis model
Nature of the activity:	Transport infrastructure – road projects (various categories: secondary, tertiary, superhighways)
Life cycle phases:	Materialization (design/construction), maintenance, and demolition
Goal definition:	To develop and apply a multi-regional LCIA framework for quantifying and comparing the environmental impacts of transportation infrastructure across different international contexts
Target audience:	Policymakers, infrastructure planners, sustainability researchers, international development agencies
Scoping:	Cradle-to-grave LCA, including raw material extraction, transport, construction, use (routine and overhaul maintenance), and end-of-life demolition; functional unit defined as 1 m^2 of paved area
Nature of inventory data:	Case-specific engineering data (materials, energy, machinery use) extracted from five real-world projects; combined with LCI databases (Ecoinvent, ELCD, USLCI) via SimaPro 8.0
Quality assessment:	Transparent assumptions (e.g., 60 km transport distance, 70% reuse at demolition), use of unified functional unit (1 m^2), equations for transport and energy normalization across countries; sensitivity acknowledged but not fully explored
Impact assessment:	• Method: Life Cycle Impact Assessment (LCIA) in accordance with ISO 14040/14044 • Software: SimaPro 8.0 • Databases: Ecoinvent, ELCD, and USLCI • Categories defined using established emission equivalency factors and regional energy conversions • Transport and energy use modeled with specific formulas; multi-indicator impact model adopted
Environmental impact categories:	• Global warming (CO_2, CH_4, etc.) • Acidification (SO_2, NOx, HF, etc.) • Eutrophication (N, P compounds) • Ecotoxicity (e.g., 2,4-D, mercury, hydrocarbons) • Smog (NOx, particles, VOCs) • Natural resource depletion (MJ surplus) • Habitat alteration (T&E count) • Ozone depletion (CFC-11 equivalents)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.12

Name:	*Assessment of environmental impacts and reduction opportunities for road infrastructures in India*
Country:	India (2024)
Assessed activity:	Construction, maintenance, and end-of-life management of Major District Roads (MDR) using flexible and rigid pavement technologies, including minor infrastructure (e.g. culverts, footpaths, signage, streetlights).
Nature of the activity:	Research study (specific solution; full LCA-based environmental assessment with improvement scenarios)
Life cycle phases:	Design, construction, maintenance, operation, and end-of-life (including recycling and materials reuse)
Goal definition:	To quantify the environmental impacts of road infrastructure in India and identify opportunities for reducing impacts via material substitution, recycling, and alternative technologies.
Target audience:	Scientists, infrastructure planners, policymakers, engineers, sustainability experts
Scoping:	• Evaluates both flexible (bituminous) and rigid (concrete) pavements. • Includes minor infrastructures (culverts, footpaths, streetlights, signage). • Assesses construction, maintenance, and end-of-life phases. • Integrates effects of deforestation (carbon sink loss), albedo, and carbonation. • Geographic focus: two MDR sections in Chhattisgarh (flexible) and Bihar (rigid). • Scale-up estimates to national-level impacts.
Nature of inventory data:	• Primary data from project reports, site engineers, road construction firms. • Secondary data from Indian-specific GaBi database. • Detailed bill of quantities for each infrastructure component. • Life cycle inventory includes: diesel, bitumen, cement, aggregates, plastic waste, lignin, steel, electricity, etc.
Quality assessment:	• Conducted sensitivity and uncertainty analysis (standard deviation < 5%) • Field-verified material usage and construction processes • Improvement scenarios validated with prior research and industry practices • Functional unit: 1 km of 7m-wide road; impacts presented per km/year and extrapolated to national scale
Impact assessment:	• Life Cycle Assessment (LCA) using GaBi 10.5 software • Impact indicators from CML methodology: ▪ Abiotic Depletion Potential (fossil)

<table>
<tr><td></td><td>▪ Acidification Potential
▪ Global Warming Potential
▪ Human Toxicity Potential
• Assessment of albedo and carbonation effects
• Accounting for carbon sink loss due to deforestation
• Two improvement scenarios (IS1 for flexible pavement, IS2 for rigid):
▪ Use of plastic waste and lignin (IS1)
▪ RDF substitution in cement production and concrete recycling (IS2)</td></tr>
<tr><td>Environmental impact categories:</td><td>• Fossil fuel depletion
• Acidification (SO_2 emissions)
• Climate change (CO_2 emissions)
• Human toxicity (DCB equivalents)
• Deforestation and associated CO_2 sink loss
• Minor infrastructure contributions (streetlights being the most impactful)</td></tr>
<tr><td>Benefit assessment methods:</td><td>• Comparison of baseline vs. improvement scenarios (IS1, IS2)
• Breakdown of % impact reductions by material or strategy
• Inclusion of recycling, alternative materials, energy substitution, and avoidance of incineration impacts
• IS1 reduced GWP by 35% for flexible pavements; IS2 reduced GWP by 19% for rigid
• Maintenance impacts reduced by ~23% for flexible pavements in IS1
• Total carbon sink loss per km estimated:
• ~76 t CO_2 eq. for flexible pavement
▪ ~228 t CO_2 eq. for rigid pavement</td></tr>
</table>

CASE STUDY NO.13

Name:	*Can rail transport-related contamination affect railway vegetation? A case study of a busy railway corridor in Poland*
Country:	Poland (2022)
Assessed activity:	Environmental contamination by potentially toxic elements (PTEs) from rail transport, and their effects on vegetation and soil health along railway corridors.
Nature of the activity:	Research study (specific solution; empirical investigation with field data and ecotoxicological assays)
Life cycle phases:	Operation and maintenance of railway infrastructure
Goal definition:	To assess the extent of contamination with heavy metals (Cu, Ni, Pb, Zn) from railway operations, its spatial variability, and its impact on plant growth (phytotoxicity), with a focus on how far pollutants spread from the track and whether side-effects (left/right of the track) distort assessments.
Target audience:	Scientists, ecotoxicologists, environmental agencies, transport planners, railway maintenance authorities
Scoping:	• Examines contamination from railway operations along a 13.5 km corridor in Stalowa Wola, Poland. • Focuses on both sides of the railway track, at distances of 0 m (track), embankment, 25 m, and 50 m. • Investigates metal concentration in soil, phytotoxicity, and ecological risk indicators. • Assesses side-effects (left/right) and defines polluted zones.
Nature of inventory data:	• 216 soil samples collected from 28 sites • Laboratory analysis of Cu, Ni, Pb, Zn (microwave digestion + flame atomic absorption spectroscopy) • Soil properties: pH, organic carbon • Phytotoxicity test using Sinapis alba (Phytotoxkit™ bioassay)

Quality assessment:	• Statistical modeling (ANOVA, PCA, correlation analysis)
	• Risk indices applied:
	  ▪ Geoaccumulation Index (Igeo)
	  ▪ Potential Ecological Risk Index (RI)
	• Side comparison analysis (left vs. right)
	• Sampling design replicated across both sides and distances for robustness

Impact assessment:	• Spatial distribution analysis of heavy metal concentrations (Cu, Ni, Pb, Zn) • Ecotoxicological bioassay for root growth inhibition • Ecological risk categorization using Igeo and RI

	• Determination of spatial dispersion patterns and environmental thresholds
Environmental impact categories:	• Soil contamination by Cu, Ni, Pb, Zn • Non-linear spatial dispersion of pollutants (most critical zone: 0–25 m) • Ecological risk: generally moderate for Cu and Pb, lower for Zn • Slight to high phytotoxicity, with some zones showing root growth inhibition >70% • Vegetation effects not strongly distance-dependent → potential for long-range effects
Benefit assessment methods:	• No formal benefit assessment framework applied • Indirect benefit explored: railway-related contamination may suppress unwanted vegetation (potential cost-saving in maintenance) • Recommendations include defining a heavily polluted buffer zone of at least 50 m from the railway and sampling both sides to avoid underestimation of contamination

CASE STUDY NO.14

Name:	*A novel approach for environmental impact assessment of road construction projects in India*
Country:	India (2024)
Assessed activity:	Construction of a 43.4 km state highway (SH-145) between Dhansura and Meghraj, Gujarat, India, including materials production, transportation, and on-site construction.
Nature of the activity:	Research study (specific solution and methodological framework using publicly available project documents for LCA)
Life cycle phases:	Design and construction (Modules A1–A5 according to ISO 21931-2).
Goal definition:	To create a transparent, replicable approach for assessing the environmental footprint of road infrastructure by combining public documents (Bill of Quantity, Analysis of Rates) with Indian environmental characterization factors.
Target audience:	Researchers, civil engineers, policymakers, environmental planners, sustainability assessors
Scoping:	• “Cradle to construction” system boundary • Use of national datasets (BOQ, AOR, ICD 2017) • 12 categories of construction item-works evaluated • Assessment of six environmental domains using LCA
Nature of inventory data:	• 197 sub-items grouped into 12 item categories • 52 road construction materials quantified via BOQ + AOR • Material-specific diesel and electricity use recorded • Characterization factors from the Indian Construction Materials Database (ICD, 2017)
Quality assessment:	• LCA aligned with ISO 14040 and ISO 21931-2 • Monte Carlo uncertainty analysis (10,000 simulations) • ±5% variation in material quantities, ±20% in characterization factors • Results normalized using CML method normalization factors
Impact assessment:	• Life Cycle Assessment (LCA) using six indicators: ▪ Energy use (MJ) ▪ Global warming potential (GWP, CO_2 eq.) ▪ Ozone depletion potential (ODP, CFC-11 eq.) ▪ Acidification potential (SO_2 eq.) ▪ Eutrophication potential (PO_4 eq.) ▪ Photochemical oxidant creation potential (POCP, ethene eq.) • Contributions from: ▪ Materials production (Modules A1–A3)

	▪ Transportation to site (Module A4) ▪ On-site construction (Module A5)
Environmental impact categories:	• Energy: 6.86 million MJ • GWP: 281 tons CO_2 eq. • ODP: 0.0134 kg CFC-11 eq. • Acidification: 2.16 tons SO_2 eq. • Eutrophication: 0.35 tons PO_4 eq. • POCP: 0.114 tons ethene eq. *Results per km. Material production phase was the hotspot (>60% in all categories except ODP).
Benefit assessment methods:	While the study does not apply a structured benefit framework, it does: • Identify material and item-level impact hotspots (bitumen, diesel, aggregates, GI pipes, steel, thermoplastics) • Suggest substitution scenarios (e.g., recycled aggregates, green asphalt alternatives, alternative fuels) • Quantify potential savings from material replacement (e.g., 4500 tons CO_2 by replacing aggregates with recycled material) • Position findings within the context of SDG progress and policy decision-making

CASE STUDY NO.15

Name:	*Life cycle assessment (LCA) and life cycle costing (LCC) of road drainage systems for sustainability evaluation*
Country:	United Kingdom (2021)
Assessed activity:	Environmental and economic assessment of ten urban drainage systems, including both traditional and sustainable urban drainage systems (SuDS), for road runoff management
Nature of the activity:	Transport infrastructure – road drainage systems
Life cycle phases:	Extraction of materials, transport, construction (civil works), operation/maintenance, and end-of-life (demolition and disposal)
Goal definition:	To propose a comprehensive LCA and LCC framework that evaluates the full life-cycle sustainability (environmental and cost) of multiple urban drainage system types under comparable conditions
Target audience:	Infrastructure designers, drainage engineers, road planners, sustainability policymakers, environmental economists
Scoping:	Cradle-to-grave LCA and LCC for ten drainage systems (e.g., swale, kerb & gully, retention pond), applied to a 1 km road section; accounts for both conveyance and storage functions; normalisation based on size and flow/storage capacity
Nature of inventory data:	Primary engineering design specifications extracted from UK DMRB guidelines; combined with emission factors from Ecoinvent 3.5 and OFFROAD2011 models; precipitation and water quality data from UK environmental agencies
Quality assessment:	Data quality addressed via pedigree matrix and Monte Carlo uncertainty analysis (1,500 runs, 95% CI); considers reliability, geographical/temporal relevance, and sample adequacy; transparent LCI breakdown into A1–A4 phases
Impact assessment:	• Method: ISO 14040/14044-compliant LCA using ReCiPe 1.10 (midpoint and endpoint levels) • Software: SimaPro 9.0 • Custom integration of OFFROAD2011 data for construction machinery emissions • Life cycle stages analyzed separately (A1–A4): materials production, transport, construction, use/maintenance/end-of-life • Impact scores derived via characterisation factors from ReCiPe midpoint/endpoint categories
Environmental impact categories:	• Climate change (GWP) • Ozone depletion • Acidification (soil and water)

	• Eutrophication • Photochemical ozone creation • Abiotic depletion (elements and fossil fuels) • Ecosystem damage (species loss), human health (DALY), and resource scarcity (endpoint indicators)
Benefit assessment methods:	• Scenario-specific identification of low-impact designs (e.g., swales, wetlands, retention ponds) • LCC integration for joint evaluation of environmental and economic performance • No monetary valuation of ecosystem services or co-benefit quantification included

CASE STUDY NO.16

Name:	*Climate change impacts assessment on railway infrastructure in urban environments*
Country:	Sweden (2024)
Assessed activity:	Reliability and risk assessment of railway infrastructure (specifically switches and crossings - S&Cs) under changing climatic conditions
Nature of the activity:	Research study (specific solution; integration of climate modeling and reliability analysis using real asset data)
Life cycle phases:	Operation and maintenance; with indirect reference to design and asset planning (focus on performance and failure behavior under climate stress)
Goal definition:	To develop and validate a methodology for assessing how climate variables affect the reliability of urban railway infrastructure assets, enabling adaptation planning based on meteorological covariates.
Target audience:	Infrastructure managers, transport authorities (e.g. Trafikverket), climate resilience planners, policymakers, railway engineers
Scoping:	• Focus on urban railway infrastructure in 40 Swedish stations • Classification into 4 climate zones using K-means clustering • Detailed analysis of Switches and Crossings (S&Cs) • Failure categorization into climatic vs. non-climatic causes • Use of climate scenarios (RCP 2.6, 4.5, 8.5) for future projections • Integration of asset databases (Trafikverket) and weather data (SMHI)
Nature of inventory data:	• Failure records and asset registry (2001–2018) • Meteorological data: temperature, humidity, wind speed, precipitation • Developed a new indicator: Climate_id to link failures with climatic events • 25 S&C assets selected in 4 representative cities (Kiruna, Boden, Borlänge, Gothenburg)
Quality assessment:	• Use of Cox Proportional Hazard Model (PHM) • Verified with statistical tests (Bartlett, Laplace, Anderson–Darling, Schoenfeld) • Sensitivity analysis on precipitation effects • Hazard function calibrated with real O&M data • Model implementation in Python, STATA, Minitab
Impact assessment:	• Cox PHM to model failure rate as function of meteorological covariates • Clustering via K-means to create climatic homogeneity groups • Sensitivity analysis on precipitation variation for reliability decline • Hazard functions customized by region and covariate set

	• Comparative analysis of median time to failure and Mean Time Between Failures (MTBF)
Environmental impact categories:	• Climate-related failure modes (e.g. snow/ice, buckling, floods, storm damage) • Service disruptions and increased maintenance needs • Asset degradation under temperature and humidity extremes • Regional variability in sensitivity to climate parameters
Benefit assessment methods:	While not a traditional benefit assessment, the study proposes: • Region-specific adaptation strategies, such as: ▪ Asset protection (galleries, heaters) ▪ Enhanced inspection regimes ▪ Drainage system upgrades • Quantified benefit of adaptation shown via reduced failure probability and increased MTBF • Strategic asset management improvements based on climatic risk profiles • Potential reduction of downtime and O&M costs through predictive planning

CASE STUDY NO.17

Name:	*Identification of Urban and Wildlife Terrestrial Corridor Intersections for Planning of Wildlife-Vehicle Collision Mitigation Measures*
Country:	Lithuania (2023)
Assessed activity:	National road network analysis to identify stable wildlife–vehicle collision hotspots based on intersections between modeled urban and wildlife corridors.
Nature of the activity:	Research study (specific solution and analytical framework based on circuit theory and spatial modeling; oriented toward mitigation planning)
Life cycle phases:	Operation and maintenance; relevant to design and long-term planning of mitigation infrastructure (e.g., fencing, overpasses)
Goal definition:	To identify stable road segments where urban development and wildlife movement corridors intersect, in order to prioritize locations for permanent wildlife–vehicle collision mitigation infrastructure.
Target audience:	Transport and environmental planners, road authorities, spatial modelers, biodiversity conservation agencies
Scoping:	• National-scale study over entire Lithuanian road network, focusing on main roads • Time series of 27,270 mammal–vehicle collisions (MVC) from 2002–2020 • Identification of 354 urban–wildlife corridor intersections using circuit theory-based modeling • Inclusion of 803.5 km of existing wildlife fencing • Wildlife corridors based on protected area connectivity, urban corridors based on urban agglomeration expansion • Road network split into 77 segments, each characterized by: ▪ No. of MVCs ▪ No. of corridor intersections ▪ Fence length
Nature of inventory data:	• CORINE land cover (CLC, 2018) • Wildlife–vehicle collision data (police and Nature Research Centre) • Spatial data on fencing, roads, traffic intensity, protected areas • Circuit theory resistance grids (urban & wildlife), permeability scoring • Corridor modeling with Linkage Mapper and Circuitscape • Decision-making with TOPSIS in ArcGIS SortViz
Quality assessment:	• Empirical validation: correlation between MVCs and corridor intersections (r = 0.75) • Use of large sample size and long-term roadkill dataset • Automated weighting in TOPSIS to avoid subjective bias

	• Resulting ranking highlights top 15 road segments for urgent mitigation

Impact assessment:	• Landscape connectivity modeling (resistance and cost-distance modeling)
	• Multi-criteria decision analysis (MCDA) using TOPSIS
	• Identification of high-risk zones based on co-occurrence of:
	  ▪ Urban–wildlife corridor intersections
	  ▪ High MVC counts
	  ▪ Existing fencing (incomplete coverage)

Environmental impact categories:	• Wildlife mortality from vehicle collisions • Landscape fragmentation • Barrier effects to wildlife movement • Functional loss of ecological connectivity • Road-related mortality in endangered species (e.g., Eurasian lynx, otter, bison)
Benefit assessment methods:	• Prioritization of 15 road sections for mitigation infrastructure (cost-effective due to partial existing fencing) • Strategic planning for multispecies overpasses and fencing closure • Proposal of permanent infrastructure based on corridor intersection "anchors" • Benefits inferred via potential reduction in MVCs and improved connectivity stability

CASE STUDY NO.18

Name:	*Improvements in high-speed rail network environmental evaluation and planning: An assessment of accessibility gains and landscape connectivity costs in Spain*
Country:	Spain (2021)
Assessed activity:	Planning and development of the Spanish High-Speed Rail (HSR) network (1990–2025), assessing trade-offs between territorial accessibility gains and habitat structural connectivity losses.
Nature of the activity:	Strategic planning evaluation (plan-level study; no direct infrastructure construction assessed, but implications across national and corridor scales)
Life cycle phases:	Planning, design (strategic scale); no assessment of construction, operation or end-of-life
Goal definition:	To quantify accessibility improvements due to HSR expansion and assess their environmental cost in terms of structural habitat connectivity loss, both at national and regional corridor levels.
Target audience:	Transport and environmental planners, policymakers, infrastructure strategists, spatial analysts
Scoping:	• Whole mainland Spain assessed in 4 time horizons: 1990, 2007, 2016, and 2025 • 8 rail corridors defined for spatial disaggregation • Accessibility measured using a gravity-based potential indicator • Structural habitat connectivity evaluated using a GIS-based landscape connectivity index • Environmental cost expressed as the % loss in connectivity per % gain in accessibility • Focused on Strategic Environmental Assessment (SEA) level
Nature of inventory data:	• GIS datasets of HSR and conventional rail lines, road networks, stations, city populations • Land use data from Corine Land Cover 1990 • Accessibility calculated for 7,970 urban centroids • Structural connectivity assessed at the pixel level (continuous habitat types)
Quality assessment:	• Longitudinal comparison using consistent methodology • Multi-scenario analysis across decades (1990–2025) • Validated connectivity metrics used in previous landscape studies • Results broken down by national level and 8 corridor regions

Impact assessment:	• Accessibility:
	  ▪ Gravity-based indicator (weighted by population, travel time with penalties)
	• Structural Connectivity:
	  ▪ Based on habitat area and effective distance between similar habitat pixels
	• Environmental Cost Analysis (AC):
	  ▪ % connectivity loss per 1% accessibility gain
	  ▪ Calculated per time period and per corridor

Environmental impact categories:	• Habitat fragmentation • Loss of landscape structural connectivity • Pressure on high-connectivity regions (e.g., interior north, northwest, and southeast of Spain) • No analysis of emissions, noise, or species-specific impacts

Benefit assessment methods:	• Indirect benefit via territorial accessibility gain (ΔA):
	  ▪ +74.7% nationally from 1990 to 2025
	• Environmental cost quantified (ΔCI):
	  ▪ −3.4% national connectivity loss in same period
	• Average cost per period:
	  ▪ 1990–2007: 0.03% CI loss per 1% accessibility gain
	  ▪ 2007–2016: 0.17% CI loss
	  ▪ 2016–2025: 0.08% CI loss
	• Corridor-level analysis identifies where infrastructure gains have highest or lowest environmental cost

CASE STUDY NO.19

Name:	*Impact of railways on land use and land cover change: Evidence from India*
Country:	India (2023)
Assessed activity:	Construction and long-term operation of the Konkan Railway (760 km railway corridor crossing ecologically sensitive areas along India's western coast)
Nature of the activity:	Empirical research study (specific solution; uses causal analysis and spatial modeling to evaluate environmental change)
Life cycle phases:	Construction and operation (with spatial focus on long-term post-construction land use impacts)
Goal definition:	To assess the causal impact of large-scale railway infrastructure on land use and land cover (LULC) using remote sensing and econometric modeling, focusing on forest, agriculture, and built-up areas.
Target audience:	Researchers, environmental planners, policymakers, infrastructure developers
Scoping:	• Study area covers 59,444 km^2 across three states: Maharashtra, Goa, Karnataka • Assesses forest cover, agricultural land, built-up/open space, and water bodies • Evaluation years: 1991 (baseline), 2003, 2008, 2014 • Compares treatment areas (4x4 km grids around railway) vs. controls (10–30 km away) • Focuses on regions with and without stations to test urbanization effects • Uses hybrid classification of satellite imagery (Landsat, IRS, Resourcesat) • Includes spatial change detection maps and fixed-effects modeling
Nature of inventory data:	• Multitemporal satellite imagery (1991–2014) • GIS land cover classification (forest, agriculture, water, built-up) • Afforestation and soil stabilization activity data from KRCL • DID grids and control zones created via spatial modeling
Quality assessment:	• High classification accuracy (Kappa ~72–93% for most classes) • Robustness checks using alternative treatment definitions (e.g. 2 km circles around stations) • Fixed effects model applied to control for time-invariant confounders • Spatiotemporal change analysis confirms observed patterns
Impact assessment:	• Difference-in-Differences (DID) regression for causal attribution • Fixed effects panel regression • Remote sensing-based land cover classification and change detection • Spatial analysis using 1 km^2 grids

Environmental impact categories:	• Forest cover: No significant negative impact; possible regeneration observed • Agricultural land: Statistically significant decline, particularly near non-station zones • Built-up/open space: Increase, especially between 2008–2014 • Water bodies: No significant change • Some regional variability observed, including horticultural expansion (e.g. coffee, teak)

Benefit assessment methods:	• No formal monetized benefit analysis
	• Positive outcomes:
	  ▪ No loss of forest cover, thanks to afforestation and mitigation measures by KRCL
	  ▪ Environmental management via vetiver grass plantation, slope stabilization
	• Infrastructure planning lesson: railways can coexist with forest ecosystems if proper management is applied
	• Emphasis on combining engineering choices with environmental safeguards

CASE STUDY NO.20

Name:	*Urban land use effects of high-speed railway network in China: A spatial spillover perspective*
Country:	China (2021)
Assessed activity:	Operation and expansion of the High-Speed Railway (HSR) network in China, with a focus on the urban land use changes induced around HSR stations.
Nature of the activity:	Research study (specific solution using spatial and econometric modeling to assess indirect land use effects)
Life cycle phases:	Operation and strategic planning (no direct construction or physical infrastructure assessment; focuses on spatial and economic spillovers)
Goal definition:	To quantify the land use spillover effects of HSR stations using nighttime light data, and to assess how effects differ based on station type (new vs. renewed) and city size.
Target audience:	Urban planners, transport economists, spatial analysts, infrastructure policymakers
Scoping:	• Study of 520 HSR stations across 180 Chinese cities (2004–2017) • Comparison between "newly built" and "renewed" stations • Use of nighttime light (NTL) data as a proxy for land use intensity • Impact analyzed within 4 km of stations (treatment) vs. 4–8 km (control) • Distinguishes impacts by city size, station location, and network connectivity • Emphasizes spatial spillover heterogeneity
Nature of inventory data:	• NTL imagery (DMSP/OLS 2004–2013 and VIIRS 2012–2017) • Station database (location, opening year, distance to center, number of trains) • Socioeconomic data: GDP, population, urban area, FDI, fixed assets • Railway network connectivity data (degree centrality, closeness, betweenness)
Quality assessment:	• Data calibration for comparability between NTL datasets • Fixed-effects panel regression model with robustness checks • Validation using event study method (parallel trends confirmed) • DID (Difference-in-Difference) regression for causal attribution • Sensitivity analysis for different distance thresholds (3–5 km)
Impact assessment:	• DID econometric modeling of treatment vs. control areas • Time-varying DID and event study regressions • Spatial network analysis using centrality metrics

	• Estimation of NTL intensity increase as proxy for land use change
Environmental impact categories:	• Urban expansion and land use intensification • Transformation of peri-urban and rural land around HSR stations • Fragmentation of agricultural land (indirect) • Regional disparities in spillover effects (urban–rural and east–west)
Benefit assessment methods:	• Land use intensity increased by 4.4% near HSR stations (on average) • Greater effects in renewed stations (in already urbanized areas) • Large cities showed stronger benefits due to economic scale and station centrality • Identified nonlinear population thresholds for spillover activation • Smaller cities risked siphoning effects, losing population/economic activity to large hubs • Recommendations for context-specific HSR planning to avoid underperformance in low-connectivity areas

CASE STUDY NO.21

Name:	*Rapid linear transport infrastructure development in the Carpathians: A major threat to the integrity of ecological connectivity for large carnivores*
Country:	Carpathian ecoregion (transnacional: Rumanía, Eslovaquia, República Checa, Polonia, Hungría, Serbia y Ucrania) (2022)
Assessed activity:	Development and expansion of road and railway infrastructure in the Carpathians, with a focus on its effects on ecological corridors for large carnivores.
Nature of the activity:	Regional policy and impact assessment study (plan-level and transboundary analysis)
Life cycle phases:	Primarily planning and design; also aborda impactos acumulativos de la construcción y operación
Goal definition:	To evaluate how rapid linear transport infrastructure (LTI) development in the Carpathians threatens ecological connectivity for large carnivores, and to propose recommendations for harmonizing grey and green infrastructure.
Target audience:	Policy makers, environmental planners, infrastructure developers, conservation biologists, EU agencies
Scoping:	• Review of transport infrastructure development and legislation across 7 Carpathian countries • Analysis of interactions between LTI and ecological corridors (using GIS data from projects like TRANSGREEN, ConnectGREEN, SaveGREEN) • Assessment of institutional, legal, ecological, and technical gaps in integrating biodiversity into transport planning • Focus on brown bear, grey wolf, and Eurasian lynx as umbrella species
Nature of inventory data:	• Spatial datasets on existing and planned LTI, Natura 2000 and Emerald sites • Habitat suitability models and resistance surfaces for large carnivores • Legal reviews of SEA/EIA/AA implementation • Case studies of green infrastructure (e.g. ecoducts, underpasses) and failures • Stakeholder interviews and project reports
Quality assessment:	• Qualitative expert review • Use of standardized ecological network modeling (connectivity, permeability) • Gap analysis across legislation, data availability, institutional capacity, and public participation

	• No empirical data collection; based on synthesis of ongoing initiatives and published literature
Impact assessment:	• Overlay analysis of ecological networks and LTI • Connectivity modeling using habitat suitability and resistance data • Cumulative impact evaluation (fragmentation, mortality, permeability loss) • Identification of barrier concentration zones (e.g. mountain valleys with LTI, settlements, electric fences)
Environmental impact categories:	• Habitat fragmentation and connectivity loss • Increased wildlife mortality due to collisions • Loss of viable gene flow and population isolation • Underperformance of SEA/EIA/AA in assessing true impacts • Lack of monitoring of mitigation measure effectiveness
Benefit assessment methods:	No formal benefit valuation, but includes: • Recommendations for harmonized legal frameworks • Best-practice examples (e.g. wildlife crossings in CZ, SK, HU, RO) • Calls for standard monitoring protocols and data transparency • Emphasis on transboundary cooperation and integrated spatial planning • Incorporation of climate change projections into future connectivity models

CASE STUDY NO.22

Name:	*Strategic environmental assessment of development corridors: The case of the Northern Economic Corridor in East Africa*
Country:	East Africa (transnacional: Uganda, Kenya, Rwanda, Burundi, South Sudan, Democratic Republic of Congo) (2024)
Assessed activity:	Master plan of the Northern Economic Corridor (NEC), a major development corridor including road, rail, port, and energy infrastructure.
Nature of the activity:	Strategic assessment (plan-level SEA applied to transboundary infrastructure planning)
Life cycle phases:	Planning (conceptual and strategic planning phases); indirect relevance to design and implementation
Goal definition:	To evaluate the procedural effectiveness of the Strategic Environmental Assessments (SEAs) conducted for the NEC master plan in Uganda and Kenya, and to provide recommendations for more strategic integration of sustainability in corridor development planning.
Target audience:	Policy-makers, planners, SEA practitioners, regional authorities, international development partners
Scoping:	• Two SEAs analyzed: one for Kenya (2016), one for Uganda (2017) • Document analysis guided by a best-practice SEA framework with 3 stages and 9 criteria • The SEAs were evaluated based on strategic alignment, objective formulation, alternative assessment, and monitoring provisions
Nature of inventory data:	• Primary data: two SEA reports (official documents) • Analytical framework includes: ▪ Strategic reference frameworks ▪ SEA objectives ▪ Baseline trend identification ▪ Strategic option analysis ▪ Monitoring and follow-up frameworks
Quality assessment:	• Both SEAs found to have limited procedural effectiveness • Key issues identified: ▪ Lack of strategic objectives and sustainability vision ▪ Poor integration of baseline trends and key drivers ▪ Alternatives not oriented toward sustainability ▪ Focus on mitigation over strategy or foresight ▪ Limited integration with planning decision windows ▪ No guidance for future SEAs or assessments

	• Kenyan SEA performed slightly better in pre-assessment framing; both lacked strategic coherence
Impact assessment:	• Qualitative content analysis • Comparison against best practice SEA criteria • No modeling or environmental impact quantification per se • Focus on process evaluation rather than outcomes
Environmental impact categories:	(Not explicitly modeled, but inferred from corridor risks): • Ecosystem fragmentation • Biodiversity loss • Pollution risks from infrastructure development • Socioeconomic inequality • Induced land-use change and migration
Benefit assessment methods:	• No quantitative benefit assessment • Strategic SEA seen as instrumental for long-term sustainable planning • Potential benefit lies in early integration of environmental and social criteria into policy and master plan formation • Paper emphasizes risk mitigation and adaptive planning as benefits of a more robust SEA

CASE STUDY NO.23

Name:	*STKDE+ approach reveals wildlife-vehicle collision hotspots at broken fence locations*
Country:	Czech Republic (2023)
Assessed activity:	Evaluation of the effectiveness of wildlife fences along highways D10 and D11 by identifying collision hotspots caused by design flaws, structural failures, or poor maintenance.
Nature of the activity:	Empirical study (specific solution; retrospective and spatial analysis of wildlife-vehicle collisions using STKDE+)
Life cycle phases:	Operation and maintenance of road infrastructure
Goal definition:	To analyze how defects in wildlife fencing (e.g., faulty endings, openings, damaged sections) contribute to wildlife-vehicle collision (WVC) hotspots and to validate the STKDE+ method for hotspot detection and mitigation assessment.
Target audience:	Road authorities, infrastructure managers, conservation biologists, transportation planners
Scoping:	• 16 highway sections analyzed (97 km total) along D10 and D11 • WVC data from 2009 to 2019 • Use of STKDE+ (spatio-temporal kernel density estimation) • Field inspections of fencing and associated structures • Hotspot classification based on cause and proximity to fence defects

Nature of inventory data:	• 571 WVC records from police and road databases
	• 54 identified fence defect sites:
	  ▪ 43 fencing endings
	  ▪ 11 structural breaches (e.g., fallen, open gates, uncovered exits)
	• Geo-referenced photo documentation of fence conditions
	• GIS data on fencing, wildlife crossings, noise barriers
	• Random control points used for statistical comparison

Quality assessment:	• High statistical significance of hotspot-fence defect correlation (Kolmogorov–Smirnov test, $p < 0.0001$) • Validation through field data and 5-year sliding window time series • STKDE+ maps revealed hotspot emergence, persistence, and disappearance patterns • Spatial accuracy sufficient to guide infrastructure retrofit or repairs
Impact assessment:	• STKDE+ spatial-temporal modeling • Classification of hotspot types: within fence, outside fence, near endings, near breaches

	• Measurement of hotspot length (~11.4 km), density (% of WVCs), and overlap with known fence defects • Comparative statistical tests against random distribution of points
Environmental impact categories:	• Wildlife mortality due to road collisions • Barrier effect and loss of ecological connectivity • Infrastructure-induced habitat fragmentation • Increased collision risk at fence failure points • Poor integration of fencing with highway exits and wildlife passages
Benefit assessment methods:	• No formal benefit valuation framework applied • Indirect benefits include: ▪ Proposal for systematic fence monitoring and maintenance ▪ Demonstration of STKDE+ as a diagnostic tool for mitigation effectiveness ▪ Potential scalability to other road networks in Europe ▪ Development of a defect database to prevent future hotspots

CASE STUDY NO.24

Name:	*Impact of road salting on Scots pine (Pinus sylvestris) and Norway spruce (Picea abies)*
Country:	Czech Republic (2021)
Assessed activity:	Assessment of environmental contamination caused by chemical winter road maintenance, focusing on accumulation of NaCl in tree needles.
Nature of the activity:	Research study (specific solution; biomonitoring using conifers as bioindicators for road salting effects)
Life cycle phases:	Operation and maintenance (specifically winter maintenance)
Goal definition:	To evaluate the accumulation of sodium (Na^+) and chloride (Cl^-) ions in Scots pine and Norway spruce near roads treated with de-icing salts, and to propose a practical contamination scale for environmental biomonitoring.
Target audience:	Environmental scientists, road maintenance planners, forestry managers, biomonitoring professionals
Scoping:	• Two study areas in the Czech Republic: ▪ Scots pine: north of Prague ▪ Norway spruce: Liberec Region • Sample distances: ▪ Close to road (<5 m) vs. control sites (>40 m) • Analysis of first-year and second-year needles • Soil samples collected up to 1.5 m from trees • Focus on 1st–3rd class roads with varying traffic intensity • Salt application range: 20–40 g/m^2 (max 60 g/m^2 per intervention)
Nature of inventory data:	• 30–32 samples per category (species, needle age, distance) • Ion concentrations of: Na, Cl, Mg, Ca, K • Soil and needle samples analyzed using ICP-MS and spectrophotometry • Control of analytical quality using reference materials (e.g., NIST 1575a, RM ION-96.4)
Quality assessment:	• Data validated with duplicate digestions and certified references • STDEV and percent error (<10%) reported • Established baseline and scale for Na and Cl concentration in needles • Temporal control via needle age classification
Impact assessment:	• Comparison of ion concentrations by: ▪ Distance from road (<5 m vs >40 m) ▪ Needle age (1st vs 2nd year) • Quantitative analysis of element accumulation trends • Cross-species comparison for sensitivity levels

	• Proposed classification scale of contamination (low, medium, high)
Environmental impact categories:	• Soil and plant contamination by NaCl • Bioaccumulation of salts in tree needles • Species-specific sensitivity to salinization • Increased vulnerability of spruce in road-adjacent forests • Potential long-term degradation of roadside ecosystems
Benefit assessment methods:	• No formal monetized benefit assessment • Indirect benefits through recommendations: ▪ Avoid planting Norway spruce near roads (due to high sensitivity) ▪ Use Scots pine as a bioindicator species ▪ Development of a contamination scale for Na and Cl in needles ▪ Emphasis on landscape resilience planning (e.g., reforestation with tolerant species) ▪ Practical guidance for road infrastructure retrofits in light of climate stress

CASE STUDY NO.25

Name:	*Comparison of the service life, life-cycle costs and assessment of hybrid and traditional reinforced concrete through a case study of bridge edge beams*
Country:	Sweden (2023)
Assessed activity:	Structural, economic, and environmental assessment of reinforced concrete bridge edge beams using traditional vs. hybrid (fibre-reinforced) concrete
Nature of the activity:	Transport infrastructure – bridge structural components
Life cycle phases:	Design, construction, operation, maintenance, and renewal (replacement); end-of-life partially considered
Goal definition:	To evaluate the service life, life-cycle costs (LCC), and environmental performance (via GHG emissions) of hybrid reinforced concrete compared to traditional reinforced concrete in bridge edge beams
Target audience:	Bridge engineers, asset managers, infrastructure planners, materials scientists, policy advisors
Scoping:	Cradle-to-gate LCA for material production; LCC includes construction, replacement, and user costs under different traffic and discount rate scenarios. Structural deterioration modeled based on chloride-induced corrosion
Nature of inventory data:	Detailed engineering parameters (design loads, concrete mix, fibre content) from field data and literature; EPDs for material GHG values from producers; simulation models for chloride diffusion and corrosion cracking
Quality assessment:	High – includes probabilistic calibration, finite element modeling, literature-derived environmental data, and extensive sensitivity analysis (discount rate, fibre price, bridge length, traffic volume)
Impact assessment:	• Environmental assessment follows ISO 14040/44 • LCA uses cradle-to-gate boundaries, EPD data from producers for concrete, steel, and fibres • Impact indicator: Global Warming Potential (GWP) only • Crack propagation modeled using finite element analysis (DIANA 10.3) • LCC conducted via present-value formula incorporating discounting, user delay costs, and multiple design-life scenarios
Environmental impact categories:	• GHG emissions from A1–A3 stages (material production) of concrete, rebar, and fibres • Higher rebar content increases GWP in traditional RC; hybrid RC reduces replacement frequency, lowering long-term impacts • Carbonation and future material decarbonization not fully modeled, but limitations discussed

Benefit assessment methods:	• Service life predictions using chloride diffusion and corrosion-induced cracking models • LCC results show up to 54% reduction in total costs using hybrid RC compared to traditional RC (depending on design and fibre price) • Hybrid RC extends service life by 58%–154% and delays replacement cycles, reducing user costs • No monetary valuation of environmental externalities included

CASE STUDY NO.26

Name:	*Impact of rail crossings on passage of Pacific salmon and steelhead in the Fraser River basin*
Country:	Canada (British Columbia, Fraser River basin) (2022)
Assessed activity:	Assessment of the impact of railway infrastructure on the connectivity of aquatic habitats for salmonid species, including Coho, Sockeye, Chinook salmon, and steelhead.
Nature of the activity:	Technical report and modeling study (specific solution with basin-scale impact modeling)
Life cycle phases:	Operation and legacy infrastructure (focused on existing rail lines and crossings)
Goal definition:	To estimate how rail infrastructure impedes salmon and steelhead access to longitudinal (stream) and lateral (floodplain) habitats and identify where remediation of railway barriers could yield significant habitat connectivity gains.
Target audience:	Wildlife and fisheries managers, infrastructure planners, conservation agencies, policy makers
Scoping:	• Study area: Fraser River basin (~10,277 km of rail with 6,242 stream crossings) • Species analyzed: Coho, Chinook, Sockeye salmon and steelhead • Methods: intrinsic potential modeling, spatial analysis, and GIS-based barrier mapping • Focused on closed-bottom culverts, assumed to be major potential barriers • Assessed 282 rail crossings affecting modeled suitable habitats
Nature of inventory data:	• GeoBC railway track line • B.C. Freshwater Atlas streams and watershed groups • B.C. Fish Passage model (bcfishpass) • Provincial Stream Crossing Inventory System (PSCIS) • Wetland and floodplain mapping datasets • Gradient, discharge, and habitat thresholds from peer-reviewed literature
Quality assessment:	• Uses validated intrinsic potential models and official geospatial datasets • Conservative estimates due to model assumptions (e.g., all closed-bottom crossings considered barriers) • Field verification not yet conducted but planned in future project phases • Limitations acknowledged (e.g. overestimation of blocked habitats, missing upgrades)

Impact assessment:	• Longitudinal connectivity:
	  ▪ Modeled barriers using stream gradients and infrastructure data
	  ▪ 1,015 km of spawning/rearing habitat potentially blocked by 282 crossings
	  ▪ 101 km of habitat blocked exclusively by rail barriers (no other obstacles)
	  ▪ 15 crossings block ~50% of all impacted habitat; 40 crossings block ~75%
	• Lateral connectivity (floodplains):
	  ▪ 13,202 ha (7.6%) of lateral habitat potentially blocked
	  ▪ 567 floodplain polygons affected
	  ▪ 48% of blocked area concentrated in 4 watershed groups

Environmental impact categories:	• Loss of habitat connectivity (both longitudinal and lateral) • Potential population fragmentation • Restricted access to spawning and rearing areas • Increased cumulative impacts from roads, dams, and trails • Disruption of floodplain ecosystem function (thermal refugia, nutrient cycles)
Benefit assessment methods:	No monetization, but provides: • Quantification of habitat potentially recoverable via targeted remediation • Basis for prioritizing rail crossing upgrades • Support for integrated, multi-barrier planning (rail + road + dams) • Strategic value in restoring high-yield habitat segments • Framework for expanding model to other BC watersheds (next steps planned)

CASE STUDY NO.27

Name:	*Road verges are corridors and roads barriers for the movement of flower-visiting insects*
Country:	Sweden (2021)
Assessed activity:	Effects of linear transport infrastructure (roads) on insect movement
Nature of the activity:	Specific solution (field-based ecological study assessing ecological functions of road verges)
Life cycle phases:	Operation (focus on existing infrastructure and its ecological implications)
Goal definition:	To understand how roads and their verges affect insect movement, and the implications for landscape connectivity
Target audience:	Road planners, ecologists, environmental managers, transport agencies
Scoping:	The system boundary includes road verges and adjacent habitats, with emphasis on landscape connectivity, species movement, and floral density
Nature of inventory data:	Field data collection (insect movement via fluorescent dye, vegetation surveys, traffic intensity from national road database)
Quality assessment:	High transparency; methods are described in detail, including sampling design, species, traffic data, statistical models, and controls
Impact assessment:	Ecological field experiment with statistical modelling (GLMM); behavioral ecology and landscape functional connectivity
Environmental impact categories:	• Biodiversity and habitat connectivity • Insect mortality risk • Movement ecology
Benefit assessment methods:	Comparative analysis (e.g., high vs. low habitat quality, traffic gradient, floral density). No monetization or standardized LCA framework was used, but strong qualitative ecological insights into mitigation potential (e.g., verge management practices)

CASE STUDY NO.28

Name:	*Methodology for Monitoring the Ecological Environment of Railway Construction*
Country:	China (2024)
Assessed activity:	Monitoring and impact assessment of railway construction projects on the ecological environment, with a focus on ecosystems, vegetation, wildlife, and spatial dynamics.
Nature of the activity:	Methodological development (specific solution; proposal and structuring of a standardized monitoring system)
Life cycle phases:	Construction phase (primary), with relevance for pre-construction baseline and post-construction follow-up
Goal definition:	To provide a scientific, systematic monitoring methodology to track and evaluate ecological impacts of railway construction, supporting environmental protection and policy implementation across different project stages.
Target audience:	Environmental planners, infrastructure developers, policy makers, railway authorities, EIA practitioners
Scoping:	• Focused on linear railway construction projects in ecologically sensitive and topographically variable regions • Monitoring plan structured into 4 stages: ▪ Preliminary survey & analysis ▪ Monitoring deployment ▪ Data collection ▪ Results interpretation • Scope includes macro and micro indicators, e.g.: ▪ Ecosystem occupation and change ▪ Plant species richness and NDVI ▪ Wildlife abundance and habitat change ▪ Presence of invasive species
Nature of inventory data:	• Remote sensing (satellite, UAV imagery) • Field survey (vegetation quadrats, camera traps, habitat mapping) • Biodiversity observation standards (HJ 710.x series) • Reference to national ecological specifications (e.g. HJ 1175-2021, invasive species list)
Quality assessment:	• Proposed methodology aligns with national technical standards and best practices • Differentiates between background vs. process monitoring, routine vs. emergency, and common vs. sensitive areas • NDVI used to compare annual vegetation changes across railway sections • Infrared cameras and manual surveys for wildlife monitoring

Impact assessment:	• Spatial overlay of railway footprint and ecosystem types • Analysis of NDVI trends over time (same location, different years) • Species diversity indices (richness, evenness, uniformity) for vegetation • Change detection in wildlife abundance and habitat fragmentation • Monitoring of alien species expansion linked to railway development
Environmental impact categories:	• Ecosystem degradation (forest, grassland, wetland occupation) • Loss of vegetation diversity and cover • Wildlife displacement and habitat alteration • Risk of invasive species expansion • Fragmentation and pressure on sensitive areas (e.g., near tunnels, stations, bridges)
Benefit assessment methods:	Not monetized; benefits derived from: • Early detection of ecological trends and project-related pressures • Site-specific design of environmental protection strategies • Institutionalization of standardized monitoring practices • Use of UAVs and remote sensing to reduce cost and increase coverage • Improvement of data-informed environmental governance

CASE STUDY NO.29

Name:	*Ecological Consequences of Railway Infrastructure Development: A Case Study of the Belgrade-Novi Sad Corridor*
Country:	Serbia (2023)
Assessed activity:	Construction and operation of the Belgrade–Novi Sad high-speed railway corridor
Nature of the activity:	Case study; methodological hybrid (qualitative and quantitative assessment at project scale)
Life cycle phases:	Construction and operation
Goal definition:	To assess the environmental susceptibility of the Belgrade–Novi Sad railway project, with emphasis on land use change, biodiversity, air and noise pollution, and hydrological impacts, while proposing mitigation strategies for sustainable railway development.
Target audience:	Policymakers, infrastructure planners, environmental managers, academic researchers
Scoping:	• Geographic extent: ~80 km corridor between Belgrade and Novi Sad, Serbia • Environments assessed: rural and urban zones, water bodies, agricultural land, and biodiversity-rich areas • Environmental parameters: ▪ Air quality (PM2.5, NO_2, VOCs) ▪ Noise pollution ▪ Biodiversity and habitat fragmentation ▪ Stormwater discharge and hydrological change • Time span of data: 2013–2022 • Analytical approaches: field measurements, GIS analysis, statistical modeling, satellite imagery, stakeholder interviews
Nature of inventory data:	• Field data: soil, water, air, biodiversity indicator • Satellite imagery analysis of land use and vegetation cover • Longitudinal datasets on air/noise pollution, rainfall, and runof • Use of Habitat Equivalency Analysis (HEA) for habitat fragmentation • Expert interviews and stakeholder engagement
Quality assessment:	• Transparent and methodologically hybrid: integrates qualitative review, fieldwork, GIS and statistical analysis • Data presented in tables and figures; e.g., correlation matrix, predictive models using decision trees and random forest algorithms • Limitations acknowledged: scope, assumptions in modeling, local specificity

Impact assessment:	• HEA for habitat loss and fragmentation assessment • GIS for sensitive area mapping and ecological corridor planning • Field and statistical data for air and water pollution analysis • Noise and stormwater runoff modeled over time (2013–2022) • Correlation matrix and R^2 used to identify key environmental drivers • Stakeholder consultations for socio-ecological validation
Environmental impact categories:	• Biodiversity loss and fragmentation • Land use change and agricultural land loss • Air and noise pollution • Hydrological pattern disruption and increased runoff • Introduction of invasive species • Ecological disconnection across rural/urban gradients

Benefit assessment methods:	• No monetization
	• Environmental benefits addressed via proposed mitigations:
	  ▪ Wildlife crossings and fencing
	  ▪ Habitat restoration
	  ▪ Vegetated buffers and retention ponds
	  ▪ GIS-informed corridor design
	  ▪ Stakeholder involvement for better socio-ecological integration
	  ▪ Promotion of green technologies and sustainable design approaches (e.g., low-noise tracks)

CASE STUDY NO.30

Name:	*Environmental balance of the high speed rail network in Spain: A Life Cycle Assessment approach*
Country:	Spain (2021)
Assessed activity:	Operation, construction, and maintenance of the Spanish high-speed rail network
Nature of the activity:	Strategic infrastructure analysis using Life Cycle Assessment (LCA); plan/corridor-level
Life cycle phases:	Design, construction, operation, and maintenance
Goal definition:	To evaluate the net environmental impacts of the Spanish high-speed rail (HSR) network across four main corridors, using LCA under a 60-year time horizon, and determine whether energy and emission reductions justify construction.
Target audience:	Transport policymakers, infrastructure planners, environmental economists, LCA practitioners
Scoping:	• Geographic scope: Spanish high speed network (3,993 km in 2023) • Corridors analyzed: Andalusia, Northern, Catalonia, Levante • Functional unit: passenger transport service (pkm/year) • Modal shift from car, bus, conventional train, and air • Environmental indicators: CO_2eq, CED, PM10, SO_2, NOx, NMVOC • Baseline + 5 sensitivity scenarios (occupancy rates, electricity mix, induced demand)
Nature of inventory data:	• Satellite and aerial imagery for infrastructure mapping • Public stats (RENFE, Fundación Ferrocarriles Españoles) • Python algorithm for passenger transport estimation • Impact coefficients from Tuchschmid et al. (2011) • Emissions data from Ecoinvent v3.7 and OpenLCA • Modal shift shares from Betancor & Llobet (2015)
Quality assessment:	• Transparent, reproducible methodology with sensitivity analysis • Consideration of modal shift, induced demand, electricity mix • Robust estimation via 105 Monte Carlo iterations for travel matrices • Assumes constant conditions over 60 years (limitation acknowledged)
Impact assessment:	• Full cradle-to-grave LCA: construction, maintenance, operation • Scenario modeling comparing HSR vs. no-HSR • Net EI = HSR burdens – avoided burdens from shifted modes • Sensitivity scenarios: S1–S5 (e.g., 100% renewables, electrified cars, demand doubling)

Environmental impact categories:	• Global Warming Potential (CO_2eq) • Cumulative Energy Demand (CED) • Human and ecological health (PM10, SO_2, NOx, NMVOC) • Note: also mention of land use, biodiversity, habitat fragmentation in discussion

Benefit assessment methods:	• Non-monetary; net benefit evaluated by years to offset construction burdens
	• Compensation thresholds:
	  ▪ CO_2eq, CED, NOx, NMVOC → 9–16 years (whole network)
	  ▪ SO_2 → 62 years
	  ▪ PM10 → 87 years (not compensated)
	• Results vary by corridor:
	  ▪ Catalonia and Andalusia: best performance
	  ▪ Levante and Northern: poor or no compensation
	• Sensitivity analysis shows:
	  ▪ Higher occupancy and renewables improve balance
	  ▪ Induced demand worsens it
	• Compared with alternatives (vehicle electrification, modal shift), HSR shows modest overall benefits

CASE STUDY NO.31

Name:	*Sustainable linear infrastructure route planning model to balance conservation and socioeconomic development*
Country:	Sri Lanka (2022)
Assessed activity:	Strategic route planning for new expressway infrastructure (Southern Expressway Extension project)
Nature of the activity:	Spatial planning and decision support model for infrastructure routing
Life cycle phases:	Planning
Goal definition:	To develop and test a spatial decision support model that balances environmental, ecological, social, and economic impacts in early infrastructure planning stages
Target audience:	Policy makers, infrastructure planners, SEA practitioners, international lending institutions (e.g. BRI actors), conservation scientists
Scoping:	Regional planning scope; 96-km expressway corridor in Sri Lanka; evaluation of multiple routing alternatives based on 23 ecological, environmental, and socioeconomic indicators
Nature of inventory data:	Spatial GIS layers (e.g. KBA, protected areas, landslide risk, soil properties, population density, road network) Satellite data (MODIS NPP, nightlights) Biodiversity layers (IUCN) Case-specific construction and accessibility data
Quality assessment:	Uses multi-criteria decision analysis, spatial resistance modeling, least-cost path analysis under three scenarios (balanced, environmental, socioeconomic). Clearly documented methodology and factor weighting.
Impact assessment:	• Spatial resistance scoring • Least-cost path modeling • Accumulated impact analysis on 23 factors • Scenario comparison (environmental, socioeconomic, balanced)
Environmental impact categories:	• Habitat loss • Biodiversity conflict (KBA, endangered spp.) • Soil erosion and landslide risk • Ecosystem fragmentation • Virus spillover potential
Benefit assessment methods:	• Scenario-based inclusion of economic indicators (nightlight, road reuse, accessibility gains, population density) • Comparative accumulated benefit scores along candidate routes

CASE STUDY NO.32

Name:	*Environmental fate of glyphosate used on Swedish railways — Results from environmental monitoring conducted between 2007–2010 and 2015–2019*
Country:	Sweden (2022)
Assessed activity:	Operation-phase management of existing railway infrastructure using herbicides (glyphosate) for vegetation control
Nature of the activity:	Maintenance
Life cycle phases:	Operation and maintenance
Goal definition:	To evaluate the mobility, persistence, and environmental fate of glyphosate and AMPA in soil and groundwater beneath Swedish railway tracks, based on national-scale monitoring data
Target audience:	Administration, environmental regulators, infrastructure managers, pesticide policy makers
Scoping:	National-scale field monitoring across 13 sites over two time periods (2007–2010 and 2015–2019); monitoring focused on groundwater and soil directly beneath and adjacent to railway tracks
Nature of inventory data:	• 603 groundwater samples and 645 soil samples • Application rates, weather data, soil physico-chemical properties • Analytical chemistry (LC-MS/MS for glyphosate and AMPA), climate and hydrological data
Quality assessment:	Longitudinal dataset, controlled sampling protocols, accredited laboratories, detailed data reporting, and temporal/statistical analysis of concentrations over time
Impact assessment:	• Concentration exceedance analysis (vs. EU GQS 0.1 µg/L) • AMPA/glyphosate ratio assessment • Temporal concentration trend analysis • Soil concentration profiles by depth
Environmental impact categories:	• Groundwater contamination risk • Herbicide persistence in soil and subgrade • Seasonal leaching influenced by weather/climate (e.g., 2018 drought)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.33

Name:	*Vulnerability assessment and lifecycle analysis of an existing masonry arch bridge*
Country:	Italy (2024)
Assessed activity:	Rehabilitation
Nature of the activity:	Assessment and retrofitting of transport infrastructure
Life cycle phases:	Operation, renewal, and maintenance
Goal definition:	To assess structural vulnerability and propose mechanical and environmental improvements for extending the service life of a historic masonry railway bridge while ensuring safety and sustainability.
Target audience:	Civil engineers, infrastructure managers, policy makers, structural and environmental analysts, heritage conservation professionals
Scoping:	Case study focused on a historic 193 m long railway masonry bridge in Southern Italy. Includes material inspections, LiDAR and drone surveys, structural and seismic modeling, cost estimation, and full LCA.
Nature of inventory data:	• Detailed field survey data (LiDAR + drone + photogrammetry) • Mechanical testing of masonry and concrete components • FE structural models (local and global) • Lifecycle inventory datasets (ISO 14040/44, Ökobau.dat, Plastics Europe)
Quality assessment:	Combines static and seismic verifications, physical material testing, kinematic collapse analysis, and lifecycle environmental modeling. Robust modeling with Midas Civil and Aedes software.
Impact assessment:	• Structural limit state verifications (static and seismic, symmetric/asymmetric loads) • Kinematic seismic collapse modeling • Lifecycle environmental impact assessment (LCA, GWP metric)
Environmental impact categories:	• Structural failure risk • Global Warming Potential (GWP tot in kg CO_2-eq/m^2) • Material degradation and durability under weather exposure • Construction vs. rehabilitation impact trade-offs
Benefit assessment methods:	• Cost-benefit analysis (retrofit vs. demolition/new build) • Environmental benefit quantification (e.g. 75% GWP reduction compared to new construction) • Performance enhancement indicators (e.g. design stress compliance post-intervention)

CASE STUDY NO.34

Name:	*Impact of dust loads in long railway tunnels: In-situ measurements and consequences for tunnel facilities and operation*
Country:	Austria (2022)
Assessed activity:	Operation-phase emissions from rail traffic inside long railway tunnels and their implications for facility maintenance and air quality
Nature of the activity:	Transport
Life cycle phases:	Operation and maintenance
Goal definition:	To quantify non-exhaust particulate matter (PM) emissions generated by rail traffic in tunnels and assess the implications for infrastructure maintenance, filter design, and environmental impact assessments
Target audience:	Rail infrastructure managers, tunnel designers, air quality experts, environmental regulators, EU transport planners
Scoping:	In-situ monitoring in a 1 km Austrian railway tunnel; includes PM concentration, chemical composition, air velocity, weather, and tunnel infrastructure (filters, electrical systems); focus on full operational context
Nature of inventory data:	• 3500+ train movements monitored over 1 year • Real-time PM measurements (TEOM & SHARP monitors) • Chemical composition sampling (metals, salts) • Tunnel-specific airflow and environmental parameters
Quality assessment:	Continuous monitoring, dual measurement instruments, statistical filtering, meteorological controls, emission factor derivation by train type
Impact assessment:	• Derivation of PM emission factors by train category • Assessment of dust-induced degradation of electrical infrastructure • Filter performance modeling (pressure loss, service life)
Environmental impact categories:	• Air quality deterioration in confined rail spaces • Risk of electrical failure due to metallic dust • Increased maintenance frequency and cost • Tunnel operation reliability and lifecycle efficiency
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.35

Name:	*Embodied greenhouse gas assessment of a bridge: A comparison of preconstruction Building Information Model and construction records*
Country:	Canada (2021)
Assessed activity:	Construction of a twin-lane highway bridge over a river, including rehabilitation and demolition of existing structures
Nature of the activity:	Construction project – bridge renewal involving demolition, reconstruction, and rehabilitation
Life cycle phases:	Construction
Goal definition:	To compare embodied greenhouse gas (GHG) emissions estimated via Building Information Modeling (BIM) versus actual on-site construction records, identifying gaps and limitations in BIM-based environmental assessments.
Target audience:	Infrastructure engineers, transport planners, sustainability assessors, BIM practitioners, and environmental policymakers
Scoping:	Case study of a completed highway bridge in Ontario, Canada. Boundaries span from material extraction to site delivery and include on-site energy use. Focused on “cradle-to-gate” emissions, excluding operation and end-of-life phases.
Nature of inventory data:	• Pre-construction BIM (Autodesk Navisworks) • QA/QC construction logs for concrete, steel, asphalt, rebar • Diesel fuel logs from general contractor • Personal communications and estimator files
Quality assessment:	Cross-referenced multiple data sources; applied 4-layer comparative approach: (1) BIM-only, (2) BIM + QA/QC data, (3) + rebar and diesel, (4) + sensitivity analysis of GHG intensity
Impact assessment:	• Embodied GHG estimation using material-specific intensity factors (SimaPro, IPCC 2013, Athena DB) • Scenario comparison (BIM baseline, adjusted quantities, on-site inclusion, sensitivity testing) • Cradle-to-gate life cycle modeling
Environmental impact categories:	• Embodied CO_2 emissions (kg CO_2e) • Construction energy use • Underestimation risks in environmental design tools
Benefit assessment methods:	• Sensitivity analysis of GHG factors • Evaluation of modeling limitations and potential improvements in BIM-based workflows • No direct benefits quantified; however, operational insights offered for future mitigation

CASE STUDY NO.36

Name:	*A PSR-AHP-GE model for evaluating environmental impacts of spoil disposal areas in high-speed railway engineering*
Country:	China (2023)
Assessed activity:	Management and environmental evaluation of spoil disposal areas (SDA) during the construction of the LN high-speed railway in Shandong
Nature of the activity:	Construction project – linear transport infrastructure with focus on SDA environmental management
Life cycle phases:	Construction
Goal definition:	To develop and apply a model (PSR-AHP-GE) for assessing environmental impacts associated with spoil disposal during railway construction, using 24 indicators to inform SDA siting and management
Target audience:	Engineers, infrastructure developers, environmental authorities, railway planners, sustainability managers
Scoping:	Case-specific: SDA in LN high-speed rail project in Shandong; full spatial and process-based scope covering environmental pressures, states, and responses
Nature of inventory data:	• Project engineering documents • Expert consultation and Likert scoring • Environmental characteristics: rainfall, slope, spoil type, erosion, vegetation, proximity to sensitive areas
Quality assessment:	Structured expert scoring, AHP validation (CR < 0.1), indicator weighting, and robust modeling approach; transparency in methodology and assumptions
Impact assessment:	• PSR framework for indicator categorization • AHP for weight determination • Grey Euclid (GE) correlation model for environmental impact level classification
Environmental impact categories:	• Soil erosion • Vegetation loss • Water pollution • Landslide and slope instability • Proximity to sensitive habitats
Benefit assessment methods:	• Response module indicators: slope protection completeness, drainage system coverage, land reclamation, forestry recovery • Indirect quantification via Level 2 environmental risk classification (elementary protective measures sufficient)

CASE STUDY NO.37

Name:	*Environmental impact assessment of high-speed railway tunnel construction: A case study for five different rock mass rating classes*
Country:	Spain (2022)
Assessed activity:	Construction of a high-speed railway tunnel (1 km, double track)
Nature of the activity:	Transport
Life cycle phases:	Construction
Goal definition:	Assess the environmental impacts associated with the construction of high-speed rail tunnels depending on rock mass rating (RMR) classes
Target audience:	Planners and designers of rail infrastructure in early project stages
Scoping:	Cradle-to-site; includes raw material extraction and processing, transport to site, and construction. Use and decommissioning phases are excluded.
Nature of inventory data:	Detailed per construction phase and RMR class. Based on EPDs, national cost databases (Adif), and author-developed tools. High data quality and traceability. Sensitivity analysis included.
Quality assessment:	Clearly defined functional unit and system boundaries. Use of standardised methodology (ISO 14040/44) and verified data sources (EPDs, official databases). Sensitivity analysis enhances robustness. Main limitation: restricted to construction phase, without inclusion of operational or end-of-life stages
Impact assessment:	Attributional, process-based LCA. Impact method: CML-IA baseline. Functional unit: 1 km of tunnel
Environmental impact categories:	• Global Warming Potential (GWP100) • Ozone Depletion Potential (ODP) • Acidification Potential (AP) • Eutrophication Potential (EP) • Photochemical Oxidation Potential (POCP) • Abiotic Depletion Potential – fossil (ADP fossil) • Abiotic Depletion Potential – elements (ADP element)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.38

Name:	*Implementation of a stochastic LCA method into BIM environment at infrastructure design projects – a case study of a bridge*
Country:	Netherlands (2023)
Assessed activity:	Environmental impact assessment of a bridge design through the integration of stochastic Life Cycle Assessment (LCA) within a Building Information Modeling (BIM) environment
Nature of the activity:	Transport infrastructure – bridge design and planning
Life cycle phases:	Design, construction, operation, maintenance, and end-of-life (full cradle-to-grave assessment covering A1–C4 modules)
Goal definition:	To develop a BIM-integrated stochastic LCA framework capable of addressing uncertainties in infrastructure projects at the early design phase and to support more sustainable design decisions
Target audience:	Infrastructure designers, engineers, sustainability consultants, public authorities (e.g., Rijkswaterstaat), and BIM specialists
Scoping:	Cradle-to-grave LCA of a Dutch bridge project using early-stage design inputs; stochastic modeling accounts for variability in material selection, transport, construction methods, operation, and EOL scenarios
Nature of inventory data:	Combination of BIM-based quantity data, expert estimates, historical project databases, and EPDs; integrates data from Revit, Dynamo, and environmental databases (e.g., NMD)
Quality assessment:	Data quality evaluated using a pedigree matrix (covering reliability, temporal/geographic/technical correlation) and Monte Carlo simulations (10,000+ iterations); sensitivity analysis also conducted
Impact assessment:	• LCA aligned with ISO 14040/44 standards • Midpoint indicators based on ReCiPe methodology • Endpoint aggregation via Environmental Cost Indicator (ECI/MKI) – used in Dutch infrastructure procurement • Stochastic modeling through Monte Carlo simulation, uncertainty propagation defined via logic-tree structure and discrete Poisson distributions • Conducted within BIM (Autodesk Revit) and parametric modeling platform (Dynamo)
Environmental impact categories:	• Climate change (GWP) • Resource depletion • Fossil fuel use

	• Waste generation • ECI/MKI as an aggregated monetary-based indicator • Variability assessed per construction element and life cycle stage
Benefit assessment methods:	• Tool identifies high-impact/high-uncertainty elements to prioritize refinement • No direct monetization or valuation of co-benefits included outside MKI

CASE STUDY NO.39

Name:	*An assessment of the potential environmental effects of bridge construction in Boga, Patuakhali, Bangladesh*
Country:	Bangladesh (2023)
Assessed activity:	Construction of a 400 m bridge over the Lohalia River (Boga Bridge)
Nature of the activity:	Specific solution
Life cycle phases:	Pre-construction, construction, operation
Goal definition:	To identify and evaluate all significant environmental effects of the Boga Bridge project using an integrated methodology (GIS, EIV, Leopold matrix, AHP)
Target audience:	Infrastructure planners, local government, and environmental authorities in charge of approving and monitoring large-scale bridge projects
Scoping:	Site-specific analysis without cradle-to-grave LCA. Covers spatial, ecological, socio-cultural and human-interest dimensions, including both construction and operational stages
Nature of inventory data:	Combination of primary data (questionnaires, interviews, participatory risk assessments, field observations) and secondary sources (literature, official reports). GIS and remote sensing tools (Landsat 9, SRTM DEM) used for environmental mapping
Quality assessment:	Comprehensive and multi-dimensional approach integrating EIV, Leopold matrix and stakeholder input. Valid use of qualitative and semi-quantitative metrics across environmental dimensions. Strong emphasis on mitigation strategies and participatory decision-making. Limitation: does not use standard LCA methodology; lacks quantitative emission or material flow data
Impact assessment:	Based on Environmental Impact Value (EIV) and modified Leopold matrix. EIV = –2; Leopold Project Impact Value = –1.51. Multi-criteria decision analysis conducted using Analytical Hierarchy Process (AHP)
Environmental impact categories:	• Land and vegetation loss • Surface water pollution • Air quality degradation • Aquatic habitat disturbance • Loss of biodiversity • Soil erosion and topsoil loss • Noise pollution • Socioeconomic displacement
Benefit assessment methods:	Evaluated qualitatively through stakeholder perception and human-interest criteria (employment generation, economic growth, road connectivity)

CASE STUDY NO.40

Name:	*Case Study on Life Cycle Assessment Applied to Road Restoration Methods*
Country:	Brazil (2023)
Assessed activity:	Environmental impact assessment of three road restoration techniques: deep recycling with cement, structural reinforcement, and Whitetopping (concrete overlay) over a 30-year life cycle
Nature of the activity:	Transport infrastructure – road restoration
Life cycle phases:	Raw material extraction, initial restoration, periodic maintenance and restoration; end-of-life excluded (study ends at 30 years)
Goal definition:	To compare environmental performance of restoration alternatives using LCA integrated with HDM-4 maintenance modeling, and inform sustainable road management decisions over 30 years
Target audience:	Transport infrastructure planners, engineers, environmental policymakers, public agencies managing road networks
Scoping:	Cradle-to-grave boundary (excluding traffic operation impacts); functional unit defined as 1 km of road (single lane with shoulder). Restorations modeled over 30 years for three road segments in Santa Catarina using HDM-4 + OpenLCA
Nature of inventory data:	Primary data from executive project specifications (SICRO/DNIT), HDM-4 simulations, and equipment consumption; secondary data from Ecoinvent v3; differentiated by road traffic intensity and restoration technique
Quality assessment:	Uncertainty and sensitivity addressed qualitatively; life cycle inventory detailed for materials, fuels, and energy; software: OpenLCA 1.10.3; normalization and weighting based on CML 2001 method
Impact assessment:	• LCA in accordance with ISO 14040/14044 • Software: OpenLCA 1.10.3 • Method: CML 2001 (midpoint-oriented, problem-based) • Aggregation by weighted average; includes 10 impact categories • Inventory includes full material and energy modeling per intervention stage from HDM-4 data
Environmental impact categories:	• Global warming (GWP) • Acidification (AC) • Eutrophication (EP) • Freshwater aquatic ecotoxicity (FAETP) • Freshwater sediment ecotoxicity (FSETP) • Marine aquatic and sediment ecotoxicity (MAETP, MSETP) • Terrestrial ecotoxicity (TAEP)

	• Human toxicity (HTP) • Photochemical oxidation (POCP)
Benefit assessment methods:	• Environmental benefits quantified as relative reductions per category • Over 30 years, deep recycling showed up to 50% lower impact than reinforcement in several categories • Whitetopping yielded significant reductions in ecotoxicity and eutrophication for high-traffic roads • No monetary valuation or external benefit assessment included

CASE STUDY NO.41

Name:	*Ballasted or ballastless for a railway infrastructure? A comparative environmental impact assessment of two solutions*
Country:	Italy (2024)
Assessed activity:	Construction and full life cycle of 1 km of single-track railway infrastructure (ballasted vs. ballastless systems)
Nature of the activity:	Specific solution
Life cycle phases:	Production, construction, maintenance, end-of-life
Goal definition:	To compare the environmental impacts of ballasted and ballastless railway superstructures over a 90-year period, using a full cradle-to-grave LCA
Target audience:	Railway infrastructure planners, operators, and public procurement agencies
Scoping:	Cradle-to-grave; includes upstream (raw material extraction, manufacturing, transport), core (construction), and downstream (maintenance and end-of-life). Use phase (operational energy) excluded as per EPD PCR guidelines
Nature of inventory data:	Primarily site-specific industrial data provided by manufacturers; complemented by Ecoinvent v3.6 database and Italferr guidelines. Includes diesel and electricity use, transport distances, material breakdown and frequency of component replacements
Quality assessment:	Comprehensive and standardised LCA following ISO 14040/44 using SimaPro and EF 3.0/EN 15804+A2 methods. Transparent and field-based inventory. Includes sensitivity analysis (lifespan, transport, rail replacement). Limitations: excludes energy use during operation
Impact assessment:	Attributional, process-based LCA using EN 15804+A2/EF 3.0 midpoint impact method (28 categories). Functional unit: 1 km of single-track infrastructure over 90 years
Environmental impact categories:	• Climate Change • Ozone Depletion • Ionising Radiation • Photochemical Ozone Formation • Particulate Matter • Acidification • Eutrophication (freshwater, marine, terrestrial) • Human Toxicity (cancer and non-cancer) • Ecotoxicity (freshwater) • Resource Use (fossils, minerals and metals) • Land Use • Water Use
Benefit assessment methods:	Environmental savings from recycling/end-of-life treatment modelled partially (transport to recovery sites included; recovery benefits excluded as per PCR)

CASE STUDY NO.42

Name:	*Life Cycle Assessment of District Heating Infrastructures: A Comparison of Pipe Typologies in France*
Country:	France (2023)
Assessed activity:	Environmental impact comparison of five district heating pipe typologies (rigid vs. flexible systems) in the Marseille Massileo network
Nature of the activity:	Urban energy infrastructure – district heating networks
Life cycle phases:	Cradle-to-grave: production, transport, construction, replacement, and end-of-life (Modules A1–A5, B4, C1–C4, D)
Goal definition:	To assess the environmental performance of different district heating pipe configurations and identify the most impactful subsystems for improved eco-design strategies
Target audience:	Infrastructure designers, urban energy planners, LCA practitioners, public authorities in sustainable infrastructure
Scoping:	Comparative LCA of 5 pipe configurations (2 rigid, 3 flexible) over a 50-year service life; functional unit: 100 m of pipeline including substations; system boundaries include pipe, trench work, water pumps, heat exchangers, and valves
Nature of inventory data:	Manufacturer data for materials; ecoinvent 3.8 for life cycle inventory; HDM-4 for trench and equipment modeling; technical datasheets for pumps and valves
Quality assessment:	High – attributional LCA using EN 15804+A1, ISO 14040/44, and French RE2020 guidance; Monte Carlo simulations, pedigree matrix, and sensitivity analyses (e.g., trench fill reuse scenario) included
Impact assessment:	• Standards: ISO 14040/44, EN 15804, XP P01-064/CN, RE2020 • Method: Attributional LCA • Characterization: Midpoint-based (CML and EN 15804 indicators) • Tool: UrbanPrint (developed by Efficacity), ecoinvent 3.8 (cut-off), Excel and Revit-Dynamo integration • Sensitivity: One-at-a-time (OAT) analysis on trench fill and component lifetimes
Environmental impact categories:	• Global warming potential (GWP) • Ozone depletion (OD) • Acidification (A) • Eutrophication (E) • Photochemical ozone creation (POC) • Abiotic depletion (elements and fossil fuels)

	• Renewable and non-renewable energy use • Net use of fresh water • Waste categories: hazardous, non-hazardous, radioactive • Output flows: reuse, recycling, energy recovery
Benefit assessment methods:	• Environmental reductions of up to 80% (rigid) and 77% (flexible) in worst-to-best comparisons • Reuse of trench filler material reduced trench impact by up to 47% and total system impact by up to 11% • No monetary valuation of environmental or social co-benefits included

CASE STUDY NO.43

Name:	*Arctic roads and railways: social and environmental consequences of transport infrastructure in the circumpolar North*
Country:	Circumpolar Arctic (case studies in Russia, USA, Canada, Finland, Norway) (2022)
Assessed activity:	Construction and operation of transport infrastructure (roads and railways) in Arctic and subarctic regions
Nature of the activity:	Cross-cutting infrastructure typology (multiple transport systems and contexts)
Life cycle phases:	Construction and operation
Goal definition:	To provide an integrated socio-ecological review of the impacts of transport infrastructure in the Arctic, including seven detailed case studies, and highlight the need for culturally and ecologically informed impact assessment
Target audience:	Policy-makers, environmental planners, engineers, Indigenous leaders and scholars concerned with Arctic development and climate adaptation
Scoping:	Narrative and case-based review; no cradle-to-grave LCA. The analysis includes social, cultural, environmental, hydrological and ecological aspects. Case studies include the Baikal–Amur Mainline, Bovanenkovo Railway, Alaska–Canada Highway, Inuvik–Tuktoyaktuk Highway, Alaska Railroad, Hudson Bay Railway, and a proposed line in Baffin Island
Nature of inventory data:	Secondary data from literature, Indigenous knowledge, environmental science, satellite data, and government reports. Spatial analysis and thematic synthesis used to assess cumulative impacts
Quality assessment:	Comprehensive multidisciplinary review synthesising academic literature, Indigenous knowledge, and engineering practices. Strong focus on ecological and cultural dimensions. Lacks quantitative impact categories or LCA approach; no functional unit or defined system boundary
Impact assessment:	No formal LCA. Impacts assessed via thematic synthesis and indicators: habitat fragmentation, permafrost degradation, pollution, species displacement, erosion, and wildfire risk
Environmental impact categories:	• Permafrost thaw and thermokarst formation • Soil erosion and sediment flow • Habitat fragmentation and wildlife migration disruption • Aquatic connectivity loss and fish migration barriers • Chemical pollution (road dust, de-icing salts, hydrocarbon spills) • Vegetation loss and spread of invasive species
Benefit assessment methods:	Considered qualitatively in terms of regional connectivity, economic access, Indigenous livelihoods, and infrastructure resilience

CASE STUDY NO.44

Name:	*Life Cycle Assessment of Bridges Using Bayesian Networks and Fuzzy Mathematics*
Country:	Spain / China / Brazil (2021)
Assessed activity:	Life cycle environmental impact of two cable-stayed bridges
Nature of the activity:	Specific solution
Life cycle phases:	Survey and design, material manufacturing, construction and installation, maintenance and operation, disassembly and recycling (full life cycle)
Goal definition:	To develop a Bayesian network and fuzzy mathematics (BNFC) framework for improving uncertainty handling in bridge LCA and compare its results with OpenLCA software output
Target audience:	LCA practitioners, bridge engineers, and researchers addressing uncertainty in infrastructure environmental assessments
Scoping:	Cradle-to-grave. Includes raw material extraction, design, construction, operation, maintenance, and end-of-life stages. Functional unit: 1 cable-stayed bridge over a 100-year lifespan
Nature of inventory data:	Combination of primary data (design contracts, construction reports, site-specific measurements) and secondary data (Ecoinvent, Bedec, literature). Processed with OpenLCA and Matlab. Robust temporal and spatial resolution
Quality assessment:	Integrates ISO-compliant LCA with advanced probabilistic and fuzzy modelling. Consistent, data-rich multi-phase inventory. Comparative analysis confirms high coherence between BNFC and software-based results. Limitation: excludes operational energy of traffic
Impact assessment:	Attributional, process-based LCA using midpoint impact indicators (GWP, AP, FEP, PMFP, WP). Combined with fuzzy evaluation to model uncertainty across five life cycle stages
Environmental impact categories:	• Global Warming Potential (GWP) • Acidification Potential (AP) • Freshwater Eutrophication Potential (FEP) • Particulate Matter Formation Potential (PMFP) • Water Consumption (WP)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.45

Name:	*Challenges and Potentials: Environmental Assessment of Particulate Matter in Spaces Under Highway Viaducts*
Country:	China (2024)
Assessed activity:	Use and environmental assessment of urban under-viaduct space (UVS) in central Shanghai
Nature of the activity:	Urban redevelopment / public space adaptation
Life cycle phases:	Operation
Goal definition:	To assess PM2.5 pollution exposure and spatial-temporal distribution in under-viaduct spaces, identify influencing factors, and propose planning recommendations for healthier spatial reuse
Target audience:	Urban planners, public health professionals, environmental engineers, and city authorities
Scoping:	Micro-environmental scale. Mobile field measurements in a selected UVS over 12 winter days (Shanghai, 2022); includes monitoring of particulate pollution and correlating meteorological and built environment factors. No material or energy flow boundaries defined
Nature of inventory data:	Primary data collected via backpack-mounted aerosol sensors and GPS; 1188 spatial PM2.5 measurements + traffic volume, meteorology, and distance indicators. High spatial and temporal resolution with validated equipment (SidePak AM520, HOBO sensors)
Quality assessment:	High-resolution mobile monitoring using validated and calibrated equipment. Multi-day dataset across working/non-working days and time periods. Comprehensive analysis (descriptive, spatial, temporal, regression). Limitations: seasonal bias (winter only); no formal LCA or emissions modelling. Robust for micro-scale exposure assessment
Impact assessment:	No formal LCA. PM2.5 exposure evaluated via relative exposure concentration (REC). Regression model identifies traffic volume, temperature, and spatial proximity to viaducts and rivers as key contributors
Environmental impact categories:	• Particulate Matter (PM2.5) concentration • Relative exposure under viaducts (REC) • Spatial dispersion gradients • Temporal variation (peak vs. off-peak, weekday vs. weekend)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.46

Name:	*Estimating CO_2 Emissions for Bus Rapid Transit (BRT) Using Life Cycle Assessment: A Case Study in Rio de Janeiro City*
Country:	Brazil (2023)
Assessed activity:	Environmental assessment of the full life cycle emissions associated with the implementation and operation of the BRT Transcarioca corridor
Nature of the activity:	Urban transport infrastructure – BRT (Bus Rapid Transit) system
Life cycle phases:	Construction, bus manufacturing, operation of infrastructure and fleet, maintenance (fleet and infrastructure); end-of-life excluded due to low data availability
Goal definition:	To quantify the net environmental impact (produced vs. avoided CO_2 emissions) of implementing the BRT corridor, based on real operational and construction data
Target audience:	Urban transport planners, sustainability researchers, public infrastructure authorities, climate policymakers
Scoping:	Cradle-to-grave LCA excluding EOL, covering 40 years; system boundaries include infrastructure (roadbed, stations, bridges), fleet (manufacturing, maintenance), fuel supply and operations; functional unit: 1 passenger-kilometer travelled (PKT)
Nature of inventory data:	High-resolution real data from Rio de Janeiro's Municipal Transport Department; includes fuel use, materials, vehicle specs, construction and operational parameters; supplemented with emission factors from IPCC, ICE, and Brazilian energy databases
Quality assessment:	High – combines empirical primary data with national emission factors; uncertainty assessed via sensitivity analysis (demand, modal shift, avoided emissions); fuel blends (biodiesel/ethanol) treated via disaggregation
Impact assessment:	• Method: Attributional LCA per ISO 14040/44 • Indicators: Single-category – Global Warming Potential (GWP) • Emission factors: IPCC 2006 guidelines, Brazilian government databases (MCTI, ANP), ICE from University of Bath • Scenario modeling for avoided emissions via modal shift and line restructuring • Functional unit: 1 PKT • Sensitivity analysis: Monte Carlo and scenario-based (± modal shift, traffic volume, system demand)

Environmental impact categories:	CO_2 emissions per life cycle phase (gCO_2/PKT)
Benefit assessment methods:	• Emissions avoided through modal shift from cars (gasoline, ethanol, CNG) and reduced conventional bus mileage • No monetary valuation or ecosystem co-benefit metrics included

CASE STUDY NO.47

Name:	*Roads of the Caribbean: regional analysis from Environmental Impact Assessments in Colombia*
Country:	Colombia (2022)
Assessed activity:	Road infrastructure projects (8 road segments or bypasses built between 2015–2017 in the Colombian Caribbean)
Nature of the activity:	Regional transport planning
Life cycle phases:	Construction and partial operation
Goal definition:	To evaluate how Environmental Impact Assessments (EIAs) for road infrastructure in the Colombian Caribbean address systemic effects such as ecological connectivity, hydrological disruption and landscape fragmentation
Target audience:	Regional planners, environmental authorities, and researchers involved in infrastructure governance and ecosystem conservation
Scoping:	No cradle-to-grave boundaries. Review of 8 EIAs in different ecological contexts; assessed using a matrix of five systemic effects (hydrological connectivity, surface drainage, groundwater flow, ecological connectivity, landscape fragmentation) across marine, wetland, dry forest, and riverine environments
Nature of inventory data:	Secondary data from project EIAs, spatial datasets, scientific literature, and expert surveys. Thematic categorisation and qualitative scoring of impacts and mitigation measures based on expert-informed matrix
Quality assessment:	Critical and structured review of EIAs using a matrix-based method informed by expert consultation. Well-documented scoring criteria. Identifies lack of integration across projects, reliance on standardised mitigation measures, and limited spatial or regional analysis. No material flow, emissions data, or LCA methodology used
Impact assessment:	No formal LCA. Systemic environmental effects assessed qualitatively via presence/absence and scale of mitigation actions in EIAs. Focused on hydrological and ecological connectivity, drainage alteration, groundwater impact, and landscape fragmentation
Environmental impact categories:	• Hydrological connectivity disruption • Surface water drainage alteration • Groundwater flow disturbance • Ecological and habitat connectivity loss • Landscape fragmentation and barrier effects
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.48

Name:	*HS2 railway, UK – route development to the hybrid bill: the environmental statement*
Country:	United Kingdom (2021)
Assessed activity:	Planning, construction and operation of the High Speed Two (HS2) railway – Phase One (London to West Midlands)
Nature of the activity:	Transport
Life cycle phases:	Construction and operation
Goal definition:	To prepare a comprehensive Environmental Statement (ES) for HS2 Phase One in accordance with UK parliamentary Standing Orders and the EU EIA Directive, reporting significant environmental effects, alternatives considered, and proposed mitigation measures
Target audience:	UK Parliament, environmental authorities, engineering consultancies, and affected communities
Scoping:	Extensive, multi-volume ES structured by geographic area (CFA reports) and thematic topics. Includes effects during construction and operation, mitigation design integration, and legal compliance. No cradle-to-grave system or material flow boundary explicitly defined
Nature of inventory data:	Based on large-scale survey campaigns, engineering designs, environmental baseline data, and modelling. GIS-supported spatial data used across 26 community areas and route-wide assessments. Combined primary and secondary data
Quality assessment:	One of the most extensive ESs ever prepared in the UK (46,000 pages). Delivered collaboratively by HS2 Ltd, EIA consultants, and engineering firms. Robust, iterative methodology aligned with ISO and EIA regulations. Limitations: not a formal LCA; lacks emission-based or midpoint category modelling
Impact assessment:	Not a traditional LCA. Environmental impacts assessed per topic and area (agriculture, air quality, noise, cultural heritage, ecology, water, etc.), using qualitative and quantitative approaches. Route-wide and local effects reported separately
Environmental impact categories:	• Air quality • Noise and vibration • Ecology and biodiversity • Landscape and visual effects • Water resources and flood risk • Cultural heritage

	• Waste and material use • Climate and carbon
Benefit assessment methods:	Considered narratively in relation to connectivity, modal shift from car/air to rail, socioeconomic development, and carbon savings assumptions (not quantitatively modelled)

CASE STUDY NO.49

Name:	*Environmental Impact Assessment Effectiveness in Public–Private Partnerships: Study on the Colombian Toll Road Program*
Country:	Colombia (2023)
Assessed activity:	Environmental assessment of 28 road PPP projects executed under Colombia's national toll road program
Nature of the activity:	National infrastructure program
Life cycle phases:	Design, construction and operation
Goal definition:	To identify causal conditions and combinations that determine Environmental Impact Assessment (EIA) effectiveness in road PPP projects using a fuzzy-set Qualitative Comparative Analysis (fsQCA) approach
Target audience:	Policy-makers, environmental licensing authorities, PPP developers and infrastructure planners
Scoping:	Assessment does not follow cradle-to-grave LCA; focuses on governance, procedural and institutional effectiveness of the EIA process. Four EIA dimensions analysed: normative, procedural, substantive and transactive
Nature of inventory data:	Data gathered from 28 PPP road cases through EIA documents, concession agreements, environmental licenses, and 30+ expert interviews. Combined with a Delphi process and content analysis of 224 scientific references
Quality assessment:	Methodologically robust. Combines empirical data, stakeholder interviews, expert validation and fsQCA modelling. Clearly structured calibration, cross-case comparison and transparent criteria. Limitation: not an LCA; does not quantify environmental emissions or resource flows
Impact assessment:	Not an LCA. Assesses effectiveness of EIA processes using four dimensions (procedural, normative, substantive, transactive). Causal analysis of drivers: consultant capacity, project features, community involvement
Environmental impact categories:	Not applicable (effectiveness dimensions of EIA processes used instead of environmental impacts)
Benefit assessment methods:	Considered through effectiveness outcomes (e.g., procedural compliance, stakeholder engagement, reduced litigation), but no quantitative benefit evaluation or scenario modelling

CASE STUDY NO.50

Name:	*Steel Bridge-Coating Systems and Their Environmental Impacts: Current Practices and Future Trends*
Country:	Canada / United States (2023)
Assessed activity:	Application and life-cycle analysis of protective coating systems for steel bridge superstructures
Nature of the activity:	Specific solution
Life cycle phases:	Production, application, maintenance and end-of-life
Goal definition:	To evaluate environmental and performance characteristics of bridge coating systems, including LCA of a typical 3-layer coating over a 64-year bridge life span, and to review current and emerging coating technologies
Target audience:	Bridge engineers, infrastructure owners, transportation authorities and materials researchers
Scoping:	Cradle-to-gate for LCA of coating ingredients, applied to the 64-year life cycle of a representative bridge. Maintenance and reapplication cycles modelled. Transport and application energy excluded
Nature of inventory data:	Combination of Safety Data Sheets (SDS), manufacturer data, Ecoinvent v3.8 database and openLCA modelling. Assumptions on bridge geometry, maintenance schedules and ingredient compositions based on regulatory and field data
Quality assessment:	High methodological transparency; LCA conducted using ISO-compliant practices and ReCiPe 2016 midpoint indicators. Robust inventory and clear functional unit (1 m^2 of coated steel). Main limitations: exclusion of coating application/removal processes and operational bridge use
Impact assessment:	Attributional LCA using openLCA. ReCiPe 2016 midpoint method applied. Focused on ingredient production and maintenance cycle impacts of a three-coat zinc-rich system
Environmental impact categories:	• Climate Change (GWP) • Fossil Depletion Potential (FDP) • Metal Depletion Potential (MDP) • Water Depletion Potential (WDP) • Particulate Matter Formation Potential (PMFP)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.51

Name:	*Sustainability-oriented assessment of pavement technologies: A case study of a heavy-traffic highway in Brazil*
Country:	Brazil (2024)
Assessed activity:	Comparative sustainability assessment of Portland Cement Concrete (PCC) and Hot Mix Asphalt (HMA) for a highway duplication project (BR-470)
Nature of the activity:	Transport infrastructure – highway pavement
Life cycle phases:	Design, material production, construction, operation/maintenance, and partial end-of-life (waste reuse assumed, but not modeled explicitly)
Goal definition:	To evaluate and compare environmental, social, and economic performance of asphalt and concrete pavement technologies in the context of developing countries
Target audience:	Road infrastructure planners, national transport agencies (e.g., DNIT), policymakers, and sustainability researchers
Scoping:	Cradle-to-use phase LCA (A1–A5, B2 stages under ISO 21930); functional unit: 1 km of road (including subbase, base, and surface layers); applied to high-traffic BR-470 corridor project
Nature of inventory data:	Foreground data from Brazilian infrastructure cost databases (SICRO), engineering designs (PROSUL), and transport distance estimates; background data from Ecoinvent 3.7.1; consistent boundary assumptions for HMA and PCC
Quality assessment:	Transparent methodology using local data and open-source tools (OpenLCA 1.10.3); normalization of impacts via CML-IA method; social impact connection through impact-to-health linkages; sensitivity analysis discussed qualitatively
Impact assessment:	• Methodology: Attributional LCA following ISO 14040/44 and ISO 21930 • Software: OpenLCA 1.10.3 • Impact method: CML-IA baseline • Indicators: 12 midpoint categories (GWP, eutrophication, acidification, toxicity, energy demand, etc.) • Normalization: CML-IA per capita/year values used for grouping results into ecosystem quality, human health, and resources
Environmental impact categories:	• GWP (PCC 68% higher than HMA) • Photochemical oxidation (PCC 33% higher) • Toxicity: PCC > HMA in all categories (e.g., 27% higher in freshwater) • Acidification and eutrophication: HMA ~10% higher • Abiotic depletion: PCC 30% lower than HMA in fossil fuel use • Cumulative energy demand: 29% higher for HMA

	• Hotspots: maintenance phase dominates across both technologies
Benefit assessment methods:	• Combined assessment of environmental impacts, health-related effects, and Net Present Value (NPV) over 20 years using ISO 15686-5 • PCC had 16% and 27% higher impacts on ecosystem quality and human health, respectively, but HMA had 30% higher impact on resource depletion • Analysis suggests PCC offers better mid- to long-term sustainability potential when incorporating green cement, CO_2 capture, or recycled aggregates • No direct monetization of environmental impacts or valuation of co-benefits, but strategic recommendations aligned with SDGs included

CASE STUDY NO.52

Name:	*Study of environmental impact from geosynthetic reinforced soil walls*
Country:	Spain / Canada (2024)
Assessed activity:	Construction of geosynthetic-reinforced soil walls (RSWs) using different types of backfill materials
Nature of the activity:	Specific solution
Life cycle phases:	Production and construction (cradle-to-gate); no operation, maintenance or end-of-life considered
Goal definition:	To assess the environmental impact of idealized polymer-strap RSWs using LCA, comparing five different backfill material scenarios across three wall heights
Target audience:	Geotechnical engineers, infrastructure designers, sustainability analysts, and public works decision-makers
Scoping:	Cradle-to-gate; includes material production, transportation, and on-site construction activities
Nature of inventory data:	Data derived from Ecoinvent v3.8, complemented by literature sources and scenario-specific equipment energy use. Modelling conducted using SimaPro v9.4.0.2 and LCA methods ReCiPe 2016 (midpoint and endpoint) and Cumulative Energy Demand (CED)
Quality assessment:	High-quality, ISO-aligned LCA with detailed material, transport and energy inventories. Uses multiple midpoint indicators and aggregated endpoint scoring. Primary limitation: does not account for service-phase impacts or end-of-life treatments. Excellent methodological transparency
Impact assessment:	Attributional, process-based LCA. Uses ReCiPe 2016 midpoint (six categories) and endpoint indicators, and CED model. Functional unit: 1 linear meter of RSW over 100-year lifespan
Environmental impact categories:	• Global Warming Potential (GWP) • Stratospheric Ozone Depletion (SOD) • Terrestrial Acidification Potential (TAP) • Human Toxicity Potential (HTP) • Freshwater Eutrophication Potential (FEP) • Marine Eutrophication Potential (MEP) • Cumulative Energy Demand (CED)
Benefit assessment methods:	Not considered directly; comparative scores allow evaluation of relative sustainability of backfill choices

CASE STUDY NO.53

Name:	*Investigations of Exhaust Emissions from Rail Machinery during Track Maintenance Operations*
Country:	Poland (2021)
Assessed activity:	Operation of diesel-powered track geometry and clearance rail maintenance vehicles
Nature of the activity:	Specific solution
Life cycle phases:	Operation
Goal definition:	To quantify real-world exhaust emissions (CO_2, CO, NO_x, HC, PM) from rail track maintenance vehicles using PEMS and assess conformity with homologation limits
Target audience:	Transport engineers, environmental regulators, rail infrastructure operators
Scoping:	Real-world operation over test routes using portable emission measurement systems (PEMS); no cradle-to-grave LCA or material flow modelling
Nature of inventory data:	Primary emission data obtained under real driving conditions with PEMS (AxionR/S+); includes two vehicle types and multiple test parameters (e.g. speed, load, distance)
Quality assessment:	Novel and robust experimental design using validated PEMS instrumentation. Includes unit, on-track and annual emissions. Limitations: based on two case vehicles only; excludes upstream/downstream life cycle stages. Strong contribution to underexplored area of maintenance machinery emissions
Impact assessment:	Not a formal LCA. Environmental performance assessed through real-time emissions of CO_2, CO, HC, NO_x, and PM. Conformity factors calculated and compared to homologation thresholds
Environmental impact categories:	• Carbon dioxide (CO_2) • Carbon monoxide (CO) • Nitrogen oxides (NO_x) • Hydrocarbons (HC) • Particulate matter (PM)
Benefit assessment methods:	Benefit assessment framework not included

CASE STUDY NO.54

Name:	*Life Cycle Assessment of a Road Transverse Prestressed Wooden–Concrete Bridge*
Country:	Czech Republic (2023)
Assessed activity:	Construction of a short-span transverse prestressed wooden–concrete bridge for road transport
Nature of the activity:	Specific solution
Life cycle phases:	Cradle-to-gate (material production, transport, manufacturing)
Goal definition:	To evaluate the environmental performance of a transverse prestressed wooden–concrete bridge (WCB) and compare it with a steel–concrete bridge (SCB) of similar size using LCA
Target audience:	Bridge designers, civil engineers, infrastructure sustainability researchers
Scoping:	Cradle-to-gate; includes raw material supply, transport to manufacturer and manufacturing processes. The functional unit is 1 m^2 of bridge surface. Bridge operation and end-of-life not considered
Nature of inventory data:	Based on measured material quantities and Ecoinvent v3.8 database; LCA performed using SimaPro 9 and IMPACT 2002+ method. Monte Carlo simulations and midpoint damage categories applied
Quality assessment:	Follows ISO 14040/44. Full material breakdown and scenario-specific modelling of two bridge types. Robust midpoint assessment and statistical uncertainty analysis. Main limitation: excludes use-phase and end-of-life impacts
Impact assessment:	Attributional LCA using IMPACT 2002+ (midpoint indicators). Comparison of WCB vs. SCB per m^2 across 15 impact categories. Dominant impacts in PM2.5 emissions, CO_2 emissions, and non-renewable energy demand
Environmental impact categories:	• Respiratory inorganics (PM2.5) • Global warming (CO_2 eq) • Non-renewable energy (MJ) • Land occupation (m^2org.arable) • Terrestrial ecotoxicity (kg TEG soil) • Carcinogens and non-carcinogens (kg C_2H_3Cl eq) • Mineral extraction (MJ surplus) • Aquatic ecotoxicity (kg TEG water) • Respiratory organics (kg C_2H_4 eq) • Ionizing radiation (Bq C-14 eq) • Ozone layer depletion (kg CFC-11 eq) • Aquatic acidification and eutrophication (SO_2/PO_4 eq)
Benefit assessment methods:	Comparative performance of WCB vs. SCB; WCB shows 28% lower total environmental damage per m^2. Benefit inferred through use of renewable material (wood) and lower steel/concrete use

CASE STUDY NO.55

Name:	*Integrated Life Cycle Assessment (LCA) of Power and Heat Supply for a Neighborhood: A Case Study of Herne, Germany*
Country:	Germany (2022)
Assessed activity:	Environmental and economic evaluation of three energy supply scenarios (base case, cost-optimized, and CO_2-optimized) for a residential neighborhood in Herne
Nature of the activity:	Urban energy infrastructure – combined electricity and heat supply system
Life cycle phases:	Full life cycle: material extraction, production, installation, use, maintenance, and end-of-life (cradle-to-grave)
Goal definition:	To develop and apply an integrated framework combining energy system modeling (ESM) and LCA to identify environmental trade-offs across scenarios for neighborhood-scale decarbonization
Target audience:	Urban planners, energy engineers, municipal authorities, LCA practitioners, climate policy advisors
Scoping:	Neighborhood-level system (48 inhabitants), including buildings, energy sources (PV, CHP, HP, gas boilers), battery storage, and grid integration; functional unit: annual energy supply (electricity + heat) for the neighborhood
Nature of inventory data:	Empirical data from municipal statistics, technical databases, academic literature, and simulations via the SESMG (open energy system modeling framework); LCA uses GaBi 9.1 and ecoinvent 3.7
Quality assessment:	Comprehensive – includes pedigree matrix for data quality, uncertainty assessment via Monte Carlo simulation, and sensitivity analysis (battery size, refrigerant types, grid export scenarios)
Impact assessment:	• Standards: ISO 14040/44 • Tool: GaBi 9.1.0.53 • Impact method: ReCiPe 2016 (H) – midpoint and endpoint • Midpoints: 17 impact categories (e.g., GWP, TA, LU, HT, MD, PM, eutrophication, ecotoxicity) • Endpoints: Damage to human health (DALY), ecosystem quality (species.yr), and resources (USD) • Monetization applied to all endpoint categories using EU and literature-based valuation approaches
Environmental impact categories:	• Climate change (CO_2eq), terrestrial acidification, photochemical ozone formation, land use, metal depletion

	• Toxicity: freshwater, marine, terrestrial ecotoxicity; human toxicity (carcinogenic/non-carcinogenic) • Water depletion, fossil depletion, stratospheric ozone depletion, particulate matter • Notably high impacts from battery storage in toxicity-related categories
Benefit assessment methods:	Scenario-based comparison: • CO_2-optimized reduced GHG by 50%, but increased ecotoxicity/human toxicity (mainly due to oversized batteries) • Cost-optimized offered lower GHG (−40%) and lowest resource use impact ▪ Monetary valuation: environmental externalities monetized (~€92,961 to €181,953/year), showing trade-offs ▪ Sensitivity analysis: reduced battery storage cut ecosystem damage by over €50,000 ▪ No biodiversity modeling or ecosystem service valuation included directly

CASE STUDY NO.56

Name:	*How much can highway stormwater ponds contribute to amphibian ecological network connectivity*
Country:	France (2022)
Assessed activity:	Stormwater pond infrastructure along highway A77 and its ecological role for amphibian species
Nature of the activity:	Specific solution
Life cycle phases:	Operation
Goal definition:	To assess whether stormwater ponds can serve as habitat stepping-stones that support ecological connectivity for amphibians in fragmented landscapes
Target audience:	Landscape ecologists, transport infrastructure planners, biodiversity conservationists
Scoping:	Site-specific, multi-scale spatial analysis focused on the ecological role of highway stormwater ponds. No cradle-to-grave LCA. Includes ecological network modeling, field surveys, and spatial connectivity metrics
Nature of inventory data:	Primary data from amphibian surveys (2018) in 33 stormwater ponds; combined with land cover data from IGN, habitat classification, graph theory–based connectivity modelling (Graphab 2.5), and environmental DNA analysis
Quality assessment:	Methodologically rigorous spatial analysis using validated biodiversity indicators, connectivity metrics (dPC, dG, BC, F), and landscape modelling. Includes both local and regional assessments. Limitations: no formal LCA; no material or emissions accounting. Strong ecological relevance but lacks functional unit or impact quantification
Impact assessment:	Not a formal LCA. Impacts assessed via functional connectivity, species richness, network metrics, and statistical correlation between habitat quality and amphibian presence
Environmental impact categories:	• Functional landscape connectivity (graph theory) • Amphibian species richness • Habitat fragmentation and isolation • Influence of land cover type on movement resistance • Potential ecological trap dynamics
Benefit assessment methods:	Evaluated qualitatively through ecological contribution to biodiversity and connectivity at local and regional scales. Role of ponds categorized as isolated, marginal, integrated, or connector

CASE STUDY NO.57

Name:	*Assessing habitat connectivity in environmental impact assessment: a case-study in the UK context*
Country:	United Kingdom (2022)
Assessed activity:	Environmental assessment of habitat connectivity for Heathrow Airport Third Runway Expansion Project
Nature of the activity:	Specific solution
Life cycle phases:	Pre-construction environmental assessment
Goal definition:	To pilot a quantitative method for assessing habitat connectivity within an Environmental Impact Assessment (EIA), using Circuitscape modelling for two species across the Heathrow Expansion Project area
Target audience:	Environmental consultants, planners, EIA practitioners, conservation ecologists and infrastructure developers
Scoping:	Baseline habitat connectivity analysis using circuit theory across an 8,523 ha study area. Focused on two species (grass snake and soprano pipistrelle). No cradle-to-grave LCA; no construction or operational phase emissions considered
Nature of inventory data:	Extensive field surveys (2017–2019), Phase 1 habitat mapping, ecological records, resistance mapping and node allocation for Circuitscape analysis. Supplemented by expert judgement and remote sensing data
Quality assessment:	Methodologically rigorous integration of ecological field data with spatial resistance modelling using Circuitscape. Includes quantitative and visual outputs to inform connectivity, mitigation and biodiversity net gain (BNG). Limitation: excludes emissions and material flows; baseline-only model; limited replicability across species
Impact assessment:	Not a formal LCA. Impacts assessed via “cumulative current” connectivity maps for each species. Highlights potential pinch-points and landscape-scale movement corridors. Enables spatial targeting of mitigation and enhancement actions
Environmental impact categories:	• Habitat fragmentation • Functional landscape connectivity • Species movement potential (for Natrix helvetica and Pipistrellus pygmaeus) • Landscape permeability and resistance • Ecological barrier and corridor effects
Benefit assessment methods:	Discussed qualitatively through spatial improvements in connectivity and habitat placement. Connectivity modelling proposed to inform biodiversity net gain strategies

CASE STUDY NO.58

Name:	*Using strategic environmental assessment and project environmental impact assessment to assess ecological connectivity at multiple scales in a national park context*
Country:	Canada (2022)
Assessed activity:	Tiered environmental impact assessment of infrastructure and management interventions in four Canadian national parks
Nature of the activity:	Multi-tier environmental planning and assessment
Life cycle phases:	Strategic planning and pre-construction assessment
Goal definition:	To evaluate how SEAs and project EIAs can be used in a tiered framework to assess and protect ecological connectivity in national parks
Target audience:	EIA practitioners, policy-makers, protected area managers, conservation scientists
Scoping:	No cradle-to-grave LCA. Multiscale approach involving SEAs (strategic), research/planning tier (intermediate), and project EIAs (local level). Focus on functional ecological connectivity rather than material/energy flows
Nature of inventory data:	Mixed methods approach including field surveys, ecological monitoring, expert consultation, GIS modelling (least-cost path, circuit theory), and SEA/EIA documentation across four case studies
Quality assessment:	Strong conceptual and methodological framework for tiered ecological impact assessment. Integration of species movement data and corridor models in SEA and research tiers. Transparent discussion of limitations and knowledge gaps. Not a formal LCA; lacks quantified emissions or material inventories
Impact assessment:	Not a formal LCA. Ecological impacts assessed through connectivity indicators (species movement, mortality, barrier mapping) and strategic frameworks. Uses Circuitscape and least-cost path modelling in several parks
Environmental impact categories:	• Habitat fragmentation • Species movement and corridor permeability • Wildlife mortality due to roads • Disruption of aquatic and terrestrial connectivity • Loss of transboundary and flyway connectivity
Benefit assessment methods:	Considered narratively through improved planning outcomes, collaborative mitigation, and alignment with biodiversity conservation goals

CASE STUDY NO.59

Name:	*Economic and environmental assessment of the Korea urban railway and its greenhouse gas mitigation potential*
Country:	South Korea (2024)
Assessed activity:	Construction, operation and end-of-life of asphalt concrete and cement concrete trackbeds for urban railway infrastructure
Nature of the activity:	Specific solution
Life cycle phases:	Construction, operation, maintenance, and end-of-life (full life cycle)
Goal definition:	To assess the environmental and economic performance of asphalt vs. cement concrete railway trackbeds using Life Cycle Costing (LCC) and Life Cycle Assessment (LCA), with a focus on greenhouse gas emissions reduction
Target audience:	Transport infrastructure planners, railway engineers, sustainability policy-makers and construction managers
Scoping:	Cradle-to-grave. Includes raw material production, transport, construction, maintenance, and demolition. Functional unit: 1 km of railway trackbed over a 50-year service life. Focused on Korean construction standards and energy systems
Nature of inventory data:	Combination of Korean-specific LCI database, construction cost manuals, IPCC emission factors, and equipment usage data. Primary parameters include asphalt/cement material properties, machinery fuel consumption, and maintenance schedules
Quality assessment:	Robust and ISO-aligned LCA using local LCI data and real-world construction figures. Transparent inventory and comparative LCC/LCA approach. Includes emission pricing and sensitivity to carbon costs. Limitation: high uncertainty in future price variables and maintenance assumptions
Impact assessment:	Attributional LCA using Korean LCI and IPCC emission factors. Carbon emissions evaluated per material and equipment usage. Asphalt concrete shows 3.36x lower emissions than cement concrete. Carbon cost monetized using EU carbon allowances
Environmental impact categories:	• Global Warming Potential (GWP – CO_2 eq) • Construction-related fuel emissions (diesel, gasoline) • Material-based CO_2 emissions (asphalt, cement, rebar) • Waste generation at end-of-life
Benefit assessment methods:	Quantified via carbon cost savings (EUR/km), reduced construction and maintenance costs, and increased durability of asphalt concrete trackbeds

CASE STUDY NO.60

Name:	*Embodied greenhouse gas assessment of railway infrastructure: the case of Austria*
Country:	Austria (2021)
Assessed activity:	Entire railway infrastructure network of Austria, with emphasis on track renewal and maintenance
Nature of the activity:	National-scale transport infrastructure
Life cycle phases:	Manufacturing, construction, maintenance, reuse/recycling (cradle-to-gate + operational maintenance; use-phase emissions excluded)
Goal definition:	To provide the first comprehensive LCA of a national railway infrastructure, combining top-down and bottom-up approaches to assess embodied GHG emissions and identify mitigation potentials under Austrian boundary conditions
Target audience:	Infrastructure managers, LCA practitioners, policy-makers, transport planners
Scoping:	Network-wide system including communication, power supply, track, tunnels, geotechnics, noise barriers, and buildings. Specific bottom-up modelling of ballasted track sections under varying traffic and curvature conditions.
Nature of inventory data:	National railway asset database (ÖBB), environmental product declarations (EPDs), maintenance logs, equipment fuel consumption, Austrian electricity mix, and region-specific emission factors. Combines real-life operational and material data
Quality assessment:	High methodological transparency; ISO-aligned LCA using country-specific data. Two-tier model (top-down and detailed bottom-up) covering diverse boundary conditions. Includes service life variability, reuse, and maintenance cycles. Limitations: excludes operational emissions and vehicle impact; focuses on GHG only
Impact assessment:	Attributional cradle-to-gate LCA. Top-down model uses annual network-wide emissions; bottom-up model computes per-km GHG emissions across sleeper types, traffic loads, and curve radii. Functional unit: per km of track and year
Environmental impact categories:	• Greenhouse gas emissions (CO_2eq) • Diesel combustion from track machinery • Material-based emissions (steel, concrete, wood) • Embodied emissions in tunnels, track and structures • Maintenance-related emissions (e.g. tamping, grinding)
Benefit assessment methods:	Evaluated monetarily (€ per tCO_2eq); mitigation potential assessed through reuse, sleeper material choice, efficient maintenance, alternative steel production methods and emission trading schemes

CASE STUDY NO.61

Name:	*Inclusion of road ecology criteria within environmental impact assessment*
Country:	Czech Republic (2024)
Assessed activity:	Road infrastructure development and its assessment under national EIA processes
Nature of the activity:	Retrospective evaluation of 52 EIA road projects for integration of road ecology criteria
Life cycle phases:	Planning and assessment (pre-EIA, notification, report, conclusion stages)
Goal definition:	To assess whether the inclusion of mitigation measures related to road ecology (e.g. wildlife-vehicle collision prevention, habitat connectivity) in Czech EIA processes has improved over time, and how consistently these are carried through different stages of the EIA process
Target audience:	EIA practitioners, transport authorities, road planners, policy-makers, ecological consultants
Scoping:	Not an LCA. Focuses on procedural quality of EIA in relation to ecological concerns, using an ex-ante framework. Assesses the inclusion of road ecology measures across temporal stages and procedural components of 52 EIA case studies between 2003–2022
Nature of inventory data:	Based on qualitative and statistical analysis of official EIA documentation (CENIA). Measures include anti-WVC mitigation, habitat connectivity improvements, and follow-up monitoring. No material flow or emissions data; relies on structured document review and binomial logistic regression analysis
Quality assessment:	Strong in methodological clarity and longitudinal scope. Uses robust data sampling and objective assessment of mitigation inclusion. Not a formal LCA; no functional unit or quantified environmental metrics. Valuable for EIA quality assessment and ecological integration monitoring. Highlights gaps in follow-up monitoring and transfer of requirements between EIA stages
Impact assessment:	Not a formal LCA. Assesses procedural and thematic inclusion of road ecology mitigation measures and monitoring (e.g. fencing, ecoducts, permeability studies). Tracks improvements in inclusion over time, but notes inconsistency in transference of requirements through EIA stages
Environmental impact categories:	• Wildlife-vehicle collisions • Landscape fragmentation and barrier effects • Loss of ecological connectivity • Habitat disturbance and degradation • Gaps in ecological follow-up monitoring
Benefit assessment methods:	Benefits inferred qualitatively via improved EIA quality, procedural consistency, and increasing inclusion of mitigation. Quantitative effectiveness of measures not directly assessed, but mitigation coverage trends and decision-stage integration analysed statistically

CASE STUDY NO.62

Name:	*Biomonitoring of heavy metal contamination with roadside trees from metropolitan area of Hefei, China*
Country:	China (2021)
Assessed activity:	Assessment of heavy metal contamination through roadside tree biomonitoring in an urban setting
Nature of the activity:	Scientific study using trees as bioindicators for environmental monitoring
Life cycle phases:	Operational monitoring (no direct infrastructure development assessed)
Goal definition:	To evaluate the bioaccumulation of heavy metals in common urban tree species (leaves and bark) as a tool for environmental impact assessment and air pollution mapping in rapidly urbanizing regions
Target audience:	Environmental scientists, urban planners, air quality authorities, ecological risk assessors
Scoping:	Not a formal LCA. Focused on field sampling of road dust and plant tissue (bark and leaves) in urban parks and roadside areas. Analysis of bioaccumulation patterns and anthropogenic sources of contamination, particularly linked to transport and industrial activity
Nature of inventory data:	Empirical field data on metal concentrations (Al, Mn, Cu, Pb, Zn, Cr, Cd, As, Ni) in dust and vegetation; calculated indices (EF, MAI); statistical analysis (ANOVA, clustering, correlation). No material or emissions inventory in LCA sense
Quality assessment:	High scientific and methodological quality. Uses standardized sampling, digestion and analysis (ICP-MS, AFS), validated with certified reference materials. Strong for biomonitoring, but not an LCA; lacks system boundary, functional unit or environmental midpoint indicators
Impact assessment:	Not a formal LCA. Impact inferred through levels of bioaccumulated metals in urban vegetation and spatial heterogeneity analysis. Highlights Cd, As, and Pb as pollutants of concern; identifies urban parks vs. roadside differences and influence of tree morphology
Environmental impact categories:	• Atmospheric heavy metal contamination • Particulate pollution from transport and industry • Bioaccumulation in urban vegetation • Ecosystem exposure and potential human health risks (indirect)
Benefit assessment methods:	Benefits discussed in terms of improved environmental monitoring capacity, tree species selection for pollution mitigation, and use of green infrastructure as a passive pollution barrier; no quantitative benefit-cost analysis

CASE STUDY NO.63

Name:	*Spatial and territorial developments for life cycle assessment applied to urban mobility — case study on Lyon area in France*
Country:	France (2021)
Assessed activity:	Daily urban passenger mobility (all modes) in the Lyon metropolitan area
Nature of the activity:	Strategic territorial life cycle assessment of urban mobility
Life cycle phases:	Cradle-to-grave (vehicle, fuel and infrastructure production, use, end-of-life)
Goal definition:	To develop and apply an interdisciplinary methodology combining LCA with a land use and transport interaction model (LUTI) to assess spatial and territorial variability in the environmental impacts of daily mobility in urban areas
Target audience:	Environmental researchers, urban planners, mobility and transport modelers, policy-makers
Scoping:	Territorial and spatialized LCA focused on person-mobility within a metropolitan region. Includes all urban transport modes (motorised, public, non-motorised), with a functional unit of "per inhabitant per day". Based on SIMBAD (LUTI) model, COPERT5 emissions model, and EcoInvent 3.2 inventory. Explores compact city and electrification scenarios
Nature of inventory data:	High-resolution spatial data from SIMBAD (mobility behaviour, socio-economic categories), vehicle fleet statistics, emission factors (COPERT5), infrastructure databases. Includes foreground and background differentiation, but not all activities within the territory. Spatialized emission maps and impact indicators are presented
Quality assessment:	Methodologically advanced and interdisciplinary. Strong coupling of LCA with spatial urban modelling. Robust foreground data on local vehicle fleets and urban form. Includes scenario analysis and GIS-based exposure estimates for NOx. Not an attributional LCA in the strict sense, but high-quality territorial environmental analysis.
Impact assessment:	Assesses seven midpoint impact categories (GWP, PMF, POF, TAP, CED, Metal depletion, Land Use) using ILCD and ReCiPe methods. Also applies GIS-based exposure mapping for NOx (at 250 m resolution). Impact transfer effects from compact city and electrification scenarios are explored
Environmental impact categories:	• Greenhouse gas emissions (CO_2eq) • Particulate matter formation (PM2.5) • Photochemical ozone (NMVOC) • Terrestrial acidification (SO_2eq) • Metal depletion (Fe-eq)

	• Land occupation and transformation • Primary energy demand
Benefit assessment methods:	Scenario-based comparison of baseline vs. compact city and electric vehicle futures. Benefits discussed in terms of GHG reduction, spatial equity, and air quality improvements. No monetary valuation; focus on emissions, exposures, and impact redistribution across urban form

CASE STUDY NO.64

Name:	*Assessment, prediction, and mitigation of metro-induced vibrations for an opera theatre adjacent to a station: a case study*
Country:	China (2023)
Assessed activity:	Operation of metro rail line adjacent to a newly constructed opera theatre
Nature of the activity:	Numerical modelling and impact mitigation study
Life cycle phases:	Operation (monitoring and impact mitigation)
Goal definition:	To develop and validate a dynamic coupling model (TTSSO) to predict metro-induced vibrations and assess the effectiveness of mitigation strategies in a sensitive building (opera theatre) located above a metro station
Target audience:	Civil and transport engineers, environmental assessment practitioners, urban planners, acoustics and vibration experts
Scoping:	Not a cradle-to-grave LCA. Focus on operational phase vibration impacts and mitigation. Application of digital twin-based dynamic modelling and field validation to guide construction and retrofitting of vibration-sensitive structures
Nature of inventory data:	Empirical data (field vibration measurements), high-fidelity FEM modelling (ABAQUS), simulation of train–track–station–soil–opera (TTSSO) system. Parameters include soil stratigraphy, train dynamic load, structural geometry and material properties. No material or emissions inventory
Quality assessment:	High scientific and technical rigor. Combines numerical and experimental approaches. Strong validation using field data. Detailed spatial and frequency-domain vibration analysis. Not a formal LCA; lacks standard environmental impact categories, but provides quantified vibration metrics and reduction performance
Impact assessment:	Not a formal LCA. Vibration levels (RMS, dB) calculated and compared with regulatory thresholds (JGJ/T170-2009, ISO 2631). Identifies vibration amplification zones and dominant frequency bands (20–40 Hz, 60–80 Hz). Pre-resonance and resonance effects analysed for structural design adaptation
Environmental impact categories:	• Structure-borne noise and vibration • Indoor environmental quality degradation • Human comfort and performance disturbance • Building integrity and resonance risk • Secondary noise during performances
Benefit assessment methods:	Benefits quantified via vibration level reduction (1–2.5 dB insertion loss) from mitigation measures (filled trench with XPS panels and building structure optimization). Compared against threshold values; performance evaluated via time- and frequency-domain metrics and contour plots

CASE STUDY NO.65

Name:	*Effects of forest roads and an assessment of their disturbance of the natural environment based on GIS spatial multi-criteria analysis: case study of the University Forest of Taxiarchis, Chalkidiki, Greece*
Country:	Greece (2023)
Assessed activity:	Forest road network development and spatial planning in a multifunctional Mediterranean forest
Nature of the activity:	Environmental assessment based on GIS and Multi-Criteria Evaluation (MCE)
Life cycle phases:	Planning and operation (focus on spatial distribution and environmental disturbance)
Goal definition:	To develop and apply a GIS-based MCE method for evaluating the environmental impact of forest roads and the capacity of the surrounding environment to absorb that impact in the University Forest of Taxiarchis
Target audience:	Forest engineers, planners, environmental managers, academic researchers, public forest authorities
Scoping:	Not an LCA. The study uses GIS and MCE methods to assess both the intensity of forest road impacts and the natural environment's absorptive capacity. Includes forestry, topographic, and social parameters; supports sustainable forest management and planning
Nature of inventory data:	Empirical spatial and attribute data from forest management plans, Corine land cover, DEM, road infrastructure, visitor data, and local authority records. Fully georeferenced and weighted indicators; no emissions or material flow inventories
Quality assessment:	Technically robust, spatially detailed, and well-integrated with national forest planning practices. Uses validated GIS layers and clearly defined weighting criteria across forestry, topography, and human-use dimensions. Not a formal LCA; lacks cradle-to-grave analysis, but strong in land use and disturbance modeling
Impact assessment:	Not a formal LCA. Impact intensity and environmental absorptiveness calculated separately, then integrated to produce a composite disturbance index. Includes road density, proximity to streams and protected areas, traffic pressure, slope, aspect, vegetation cover, productivity, and tourism infrastructure
Environmental impact categories:	• Forest habitat disturbance • Landscape fragmentation and soil instability risk • Proximity impacts on hydrology and riparian systems

	• Terrain-related vulnerability (steep slopes, elevation) • Anthropogenic pressures (visitor density, road use intensity)
Benefit assessment methods:	Spatial decision support for forest road optimization. Benefits derived from the application of GIS-MCE methodology for reducing ecological disturbance, improving forest accessibility planning, and supporting compliance with sustainability goals (SDG 12)

CASE STUDY NO.66

Name:	*Environmental impact assessment based on particulate matter, and chlorophyll content of urban trees*
Country:	Hungary (2024)
Assessed activity:	Traffic-related air pollution in urban environments
Nature of the activity:	Empirical biomonitoring of particulate deposition using urban trees
Life cycle phases:	Operation (monitoring-focused study; no infrastructure construction assessed)
Goal definition:	To assess air pollution along an urban transect using leaf-deposited dust and chlorophyll content of Celtis occidentalis as bioindicators, with emphasis on traffic proximity and meteorological effects
Target audience:	Environmental scientists, urban ecologists, air quality authorities, urban planners
Scoping:	Not a formal LCA. Study of environmental impacts of vehicle emissions on urban vegetation. Monitors spatial variation of dust load and leaf pigment response along a 400 m urban road section between a busy intersection and a suburban endpoint
Nature of inventory data:	Empirical sampling of leaf dust (μg/cm^2) and chlorophyll content (mg/g) in July and September 2022; statistical analysis (correlation, regression, t-tests). Includes meteorological and land use data, but no emissions inventory or material flows
Quality assessment:	Scientifically rigorous and reproducible. Strong field protocol with repeated seasonal sampling, validated analytical techniques, and robust statistical treatment. Not a formal LCA; lacks functional units, system boundary, or impact categories per ISO standards. Valuable for urban bioindication and ecosystem service studies
Impact assessment:	Not a formal LCA. Impacts assessed via particulate deposition trends and chlorophyll variation in tree leaves in relation to traffic intensity and precipitation. Regression models capture spatial pollutant patterns and urban tree physiological responses
Environmental impact categories:	• Particulate matter (PM10, dust deposition) • Urban air pollution (traffic-related) • Chlorophyll response and photosynthetic stress • Vegetative filtering of airborne particles • Meteorological effects on deposition (rain wash-off)
Benefit assessment methods:	Benefits discussed in terms of bioindicator application, ecosystem service evaluation (air purification), and cost-effective air quality monitoring. No economic valuation; findings support green infrastructure planning and adaptive sampling strategies

CASE STUDY NO.67

Name:	*Quantitative Analysis of Carbon Emissions from Highway Construction Based on Life Cycle Assessment*
Country:	China (2024)
Assessed activity:	Quantification of CO_2 emissions from highway construction using a binary statistical method based on real-world activity data
Nature of the activity:	Transport infrastructure – expressway construction
Life cycle phases:	Raw material production and on-site construction (transportation excluded); end-of-life not considered
Goal definition:	To develop and validate a statistical method for estimating CO_2 emissions during highway construction using actual construction data, and to identify emission hotspots for carbon reduction strategies
Target audience:	Transportation agencies, infrastructure project managers, LCA practitioners, national policy advisors
Scoping:	System boundary includes cradle-to-site stages (material production + on-site construction); functional unit: 1 km per lane ($t \cdot km^{-1} \cdot lane^{-1}$); applied to a 122 km four-lane expressway in central China with a high bridge-to-tunnel ratio
Nature of inventory data:	Binary statistical method combining monthly energy and material consumption data from 61 contractors; validated against third-party audits (e.g., 0.42% deviation for electricity)
Quality assessment:	High – detailed inventory with quality control at three levels (contractor, supervision company, project management); emission factors from IPCC and national/local studies; real consumption data ensured accuracy and replicability
Impact assessment:	• Method: Attributional LCA according to ISO 14040/44 • Indicators: Single impact category – Global Warming Potential (CO_2 only) • Emission factors: National LCI and literature-derived CO_2 emission coefficients for materials (cement, steel, bitumen, etc.) and fuels (diesel, electricity, LNG) • No software/tool specified; calculations performed via custom spreadsheet methods • Includes contribution, intensity, and correlation analysis (e.g., cement use vs. emissions)
Environmental impact categories:	• Total emissions: 10,605.2 $t \cdot km^{-1} \cdot lane^{-1}$ • Material production phase: 95.2% of total emissions ▪ Main contributors: steel (57.5%), cement (41.5%)

	▪ Main sources: diesel (59.4%), electricity (32.8%), LNG (5.3%) ▪ Tunnel construction (643.3 t·km^{-1}·lane^{-1}) highest among engineering types ▪ Emission hotspots: pile foundations, tunnel excavation, asphalt surfacing, preventive subgrade works
Benefit assessment methods:	• Indirect benefits evaluated via hotspot identification for targeted reduction • Correlation analysis (cement P.O. 42.5 use vs. emissions) used for predictive estimation • Emission intensity metrics used to identify high-impact activities with relatively low material volumes • No monetary or external benefit valuation included

CASE STUDY NO.68

Name:	*LCA of Different Construction Choices for a Double-Track Railway Line for Sustainability Evaluations*
Country:	Italy (2023)
Assessed activity:	Design, construction and maintenance of a double-track railway line
Nature of the activity:	Comparative life cycle assessment (LCA) and life cycle cost (LCC) of construction and maintenance alternatives
Life cycle phases:	Material production, construction, maintenance, end-of-life (use phase excluded)
Goal definition:	To evaluate the environmental and economic performance of alternative construction materials and maintenance strategies for railway infrastructure through LCA and LCC methodologies
Target audience:	Transport infrastructure planners, engineers, environmental analysts, decision-makers involved in railway sustainability
Scoping:	Cradle-to-end-of-life LCA of 1 km railway infrastructure, using two track typologies (embankment and cut). Compares 10 scenarios with virgin vs. recycled materials (RAP), and with/without lime stabilization. Assumes identical use phase across scenarios. Analysis includes two maintenance plans (every 5 vs. 10 years)
Nature of inventory data:	Based on EcoInvent datasets in SimaPro and PaLATE software, including foreground data from real Italian railway projects. Emissions, energy, material use, and transport distances are modelled per ISO 14040/14044 standards. Includes rail, sleepers, ballast, sub-ballast, soil, RAP, lime, and fuel consumption
Quality assessment:	High methodological quality. ISO-compliant LCA supported by two software tools (SimaPro and PaLATE). Functional unit well defined; sensitivity analysis and scenario comparison included. Comprehensive impact categories and maintenance effects considered. Monetization via LCC follows EC external cost guidelines
Impact assessment:	Conducted using multiple indicators (GWP, NOx, PM10, acidification, abiotic depletion, water scarcity, etc.). Results indicate construction phase dominates impacts (>80%), especially material production. Use of RAP and lime reduces GWP and NOx, but lime increases PM10 due to fine dust
Environmental impact categories:	• Global warming potential (CO_2eq) • Nitrogen oxides (NOx) • Particulate matter (PM10)

	• Acidification (SO_2eq) • Heavy metals (Hg, Pb) • Eutrophication (PO_4eq) • Abiotic resource depletion (fossil and elemental) • Water scarcity • Ozone layer depletion
Benefit assessment methods:	Quantified via LCA and LCC. Environmental benefits estimated as % reductions vs. reference case. Economic externalities monetized (e.g. pollution, user time, vehicle operation, agency costs). Use of RAP and lime enables emissions and cost savings; SimaPro outputs considered more reliable than PaLATE for rail specifics

CASE STUDY NO.69

Name:	*Quantifying the Environmental Impact of Vehicle Emissions Due to Traffic Diversion Plans for Road Infrastructure Construction Projects: A Case Study in China*
Country:	China (2023)
Assessed activity:	Temporary traffic diversion due to urban bridge construction
Nature of the activity:	Environmental impact quantification of vehicle emissions from traffic detours
Life cycle phases:	Use phase (during infrastructure construction)
Goal definition:	To propose and apply a method for quantifying environmental impacts of vehicle emissions caused by traffic congestion and detours during road infrastructure construction, using a case study in Chongqing
Target audience:	Urban planners, transport engineers, environmental analysts, LCA researchers, policy-makers
Scoping:	Not a full LCA. Consequential analysis focused on additional emissions from traffic rerouting. Considers traffic speed, road saturation, and detour length. Uses ReCiPe 2016 (midpoint and endpoint) and COPERT V emission model under Chinese traffic standards. Focused on on-road hot emissions only
Nature of inventory data:	Empirical traffic data (speeds, flows, congestion), route lengths, emission factors from COPERT V model (Euro 5/China 5 standard). Ten pollutant types modelled (CO, NOx, VOCs, CH_4, PM, CO_2, SO_2, N_2O, NH_3, NMVOC). Life cycle inventory built for four detour plans with scenario comparison
Quality assessment:	Technically robust and methodologically novel. Combines real traffic data, validated models, and ReCiPe 2016 for midpoint and endpoint evaluation. Incorporates Sobol sensitivity analysis. Not a cradle-to-grave LCA; excludes material flows and infrastructure emissions. High resolution in traffic-based emissions impact
Impact assessment:	Environmental impacts estimated via ReCiPe 2016 (hierarchist). Key categories include global warming, ozone formation, acidification, particulate matter, and ozone depletion. Endpoints: DALYs and species.year. Plan D showed highest impact. Global warming dominated both human health and ecosystem endpoints
Environmental impact categories:	• Global warming (CO_2 dominant) • Fine particulate matter formation • Human health ozone formation • Terrestrial acidification • Ecosystem ozone formation

	• Stratospheric ozone depletion
Benefit assessment methods:	No direct benefit modelling. Indirect benefits inferred from comparison between traffic diversion plans; tool supports early-stage planning decisions to reduce environmental impact of detours. Future benefits discussed in context of electric vehicle transitions and improved traffic modelling accuracy

CASE STUDY NO.70

Name:	*Environmental assessment of some heavy metals in selected medicinal plant species along a busy road in Vrnjačka Banja, Serbia*
Country:	Serbia (2022)
Assessed activity:	Traffic-induced heavy metal contamination in vegetation near busy roads
Nature of the activity:	Empirical environmental contamination assessment using medicinal plants as bioindicators
Life cycle phases:	Operation (impact from road traffic emissions)
Goal definition:	To assess the concentration and distribution of Pb, Cr, Cd and Mn in medicinal plants growing at different distances from a heavily trafficked road, and determine spatial variation in bioaccumulation
Target audience:	Environmental health researchers, ecotoxicologists, roadside vegetation managers, public health authorities
Scoping:	Not a formal LCA. Compares plant samples collected a few meters and 500 meters from road E-761 in Vrnjačka Banja. Focuses on root, stem and leaf content in four plant species; evaluates soil background levels and health risk relevance
Nature of inventory data:	Field-collected plant and soil samples; heavy metal concentrations determined by atomic absorption spectrophotometry (AAS). Statistical analysis using ANOVA and Fisher's LSD test. No material flow or emissions inventory
Quality assessment:	Scientifically rigorous with replicated sampling and validated analytical methods. Strong statistical treatment and species-level detail. Not a formal LCA; lacks system boundaries, functional units, or environmental impact categories per ISO standards. Strong for contamination pattern assessment and bioindicator application
Impact assessment:	Not an LCA. Evaluates variation in metal uptake by plant part and species. Found decreasing gradient with distance from road. Root tissues had highest metal content. Soil metal concentrations remained below legal thresholds. Traffic identified as main source of Pb, Cr, Cd and Mn near road
Environmental impact categories:	• Heavy metal accumulation (Pb, Cr, Cd, Mn) • Soil-to-plant metal transfer • Phytotoxicity and physiological stress in plants • Spatial pollution gradients related to traffic proximity • Potential risk to human health via medicinal plant use
Benefit assessment methods:	Benefits inferred through use of local plant species as bioindicators for environmental monitoring. Safety of medicinal plant use discussed relative to WHO standards. No quantitative benefit or mitigation modelling

CASE STUDY NO.71

Name:	*Comparative Life Cycle Analysis of Concrete and Composite Bridges Varying Steel Recycling Ratio*
Country:	Spain (2021)
Assessed activity:	Bridge construction and maintenance, comparing four bridge deck types across different span lengths
Nature of the activity:	Cradle-to-end-of-life life cycle assessment (LCA) of structural alternatives in bridge design
Life cycle phases:	Manufacturing, construction, use and maintenance, end of life
Goal definition:	To assess the environmental performance of four bridge deck types across different span lengths, with focus on the role of steel recycling ratio in composite structures
Target audience:	Structural and civil engineers, sustainability analysts, transport infrastructure designers, policy-makers
Scoping:	ISO 14040-compliant LCA comparing prestressed concrete solid slab (PCSS), lightened slab (PCLS), prestressed concrete box-girder (PCBG), and composite box-girder (CBG). Scenarios differ in structural span (15–40 m) and steel recycling ratios (71%, 90%, 98%)
Nature of inventory data:	Quantitative inventory from real projects, EcoInvent v3.3, OpenLCA and PaLATE software. Includes material inputs (concrete, rebar, structural steel), diesel use, machinery energy, transport distances, and carbonation. Functional unit: 1 m^2 of bridge deck
Quality assessment:	High technical and methodological quality. Includes midpoint and endpoint ReCiPe 2008 assessments, Monte Carlo uncertainty analysis, and comparative evaluation by span length. Functional unit clearly defined. Strong integration of recycling scenarios and maintenance modelling. Full LCA scope covered
Impact assessment:	Impact indicators include GWP, PM10, acidification, metal depletion, water use, eutrophication, human/ecotoxicity, and resource depletion. Key drivers: material quantities, recycling ratio, maintenance frequency, carbonation. Composite decks favored when steel recycling >90%
Environmental impact categories:	• Global warming potential (CO_2eq) • Particulate matter formation • Fossil and metal resource depletion • Human and ecotoxicity • Acidification, eutrophication (freshwater/marine) • Land and water use, ozone depletion

	• Carbonation-related CO_2 capture in end-of-life phase
Benefit assessment methods:	Benefits quantified by normalized impact scores and scenario comparisons. Composite bridges with 98% steel recycling offer lowest total impact for >25 m spans. Concrete alternatives favored below 17 m. Carbonation, recycled material use, and maintenance strategy critical in result differentiation

CASE STUDY NO.72

Name:	*Operational and Environmental Assessment of Weaving Section for Urban Roads: Case Study, Aljouf Region, KSA*
Country:	Saudi Arabia (2023)
Assessed activity:	Urban road weaving section operation and traffic impact simulation
Nature of the activity:	Microsimulation-based traffic capacity and exhaust emission assessment
Life cycle phases:	Operation (focus on dynamic traffic flow and emissions under construction-related disruptions)
Goal definition:	To analyze how geometric and traffic characteristics (weaving length, heavy vehicle percentage, volume ratio) influence road capacity and exhaust emissions in urban weaving sections, using microsimulation modelling
Target audience:	Urban transport planners, traffic engineers, road authorities, sustainability researchers
Scoping:	Not a formal LCA. Combines VISSIM-based microsimulation with regression analysis to estimate traffic throughput and emissions (CO, NOx, HC) under different geometric and demand scenarios. No cradle-to-grave emissions or material inventory
Nature of inventory data:	Field data from Sakakah–Dumat Al-Jandal Road (main arterial with service lanes), traffic volume and composition, weaving length, simulation results from VISSIM 9.00. Exhaust emission factors derived through vehicle movement simulations (not COPERT or LCI based)
Quality assessment:	Methodologically strong in traffic simulation and statistical modelling. Calibrated and validated with field travel time data. High R^2 values for regression models (capacity: 0.967; emissions: 0.995). Not an LCA; lacks functional unit or impact category normalization. Valid for operational and emissions trend prediction under urban road conditions
Impact assessment:	Not an LCA. Focuses on emissions linked to lane-changing turbulence in weaving zones. Demonstrates that higher volume ratios and heavy vehicle shares significantly increase emissions and reduce capacity. Regression models quantify effects of volume ratio and weaving length
Environmental impact categories:	• Exhaust emissions: CO, NOx, HC • Traffic congestion and operational delay • Emission variation with geometric configuration
Benefit assessment methods:	Emissions and capacity benefits evaluated via comparison across 160 simulation scenarios. Mathematical models provided to inform planning. No monetary valuation; results intended for decision support in weaving section design

CASE STUDY NO.73

Name:	*Numerical analysis of a multi-objective maintenance decision-making model for sustainable highway networks: Integrating the GDE3 method, LCA and LCCA*
Country:	China (2023)
Assessed activity:	Multi-objective optimization of pavement maintenance strategies for a highway network using a novel model integrating Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCCA), and GDE3 optimization algorithm
Nature of the activity:	Transport infrastructure – highway pavement maintenance planning
Life cycle phases:	Construction, maintenance, rehabilitation; partial end-of-life (EOL considered indirectly in cost and emission estimations)
Goal definition:	To develop a decision-support model (PM-GDE3) for optimizing highway pavement maintenance strategies by minimizing costs, carbon emissions, and energy consumption while maintaining service quality
Target audience:	Highway infrastructure planners, pavement engineers, LCA practitioners, public works authorities, and policy developers
Scoping:	Cradle-to-site system boundaries covering 1 km of single-lane asphalt pavement; maintenance scenarios modeled over 30 years for the Guangdong highway network; functional unit: 1 km-lane
Nature of inventory data:	Local empirical data from Guangdong highway authority (traffic, pavement performance, maintenance records); carbon/energy data from literature and emission factors; material and energy consumption estimated from actual project data and national datasets
Quality assessment:	High – includes real case data, pavement prediction models (R^2 > 91%), Monte Carlo simulations, pedigree matrix, and comparison with conventional tool (PAVER); uncertainty handled through elite set strategies and sensitivity scoring
Impact assessment:	• Methodology: Attributional LCA + LCCA compliant with ISO 14040/44 • Tools: Custom model implemented with jMetal (v5.10) for optimization and in-house LCA calculations • Optimization method: Generalized Differential Evolution 3 (GDE3) for multi-objective problem solving • Objectives: Minimize cost (CNY), carbon emissions (t CO_2), and energy use (MJ); ensure pavement performance indices (PCI, RDI, RQI, SRI) exceed thresholds • Scenario simulations over 30 years, including dynamic treatment selection (e.g., micro-surfacing, ultra-thin friction course, fog seal)

Environmental impact categories:	• Global Warming Potential (GWP – CO_2 emissions) • Energy consumption (MJ) • Emissions breakdown by treatment type (e.g., rehabilitation vs. preservation) • Hotspots: milling & filling and full-depth reclamation had the highest emissions; preservation actions prioritized to minimize impacts
Benefit assessment methods:	• Final solutions ranked via weighted scoring of environmental, economic, and performance criteria • Preventive strategies reduce long-term deterioration and maximize lifecycle performance • No direct monetization of ecosystem or external co-benefits included

CASE STUDY NO.74

Name:	*Environmental assessment of road freight transport services beyond the tank-to-wheels analysis based on LCA*
Country:	Colombia, Malaysia, Spain (2024)
Assessed activity:	Road freight transport services across different geographical and regulatory contexts
Nature of the activity:	Comparative life cycle assessment of road freight services including vehicle, fuel, infrastructure and traffic
Life cycle phases:	Vehicle manufacturing, infrastructure construction, fuel production, operation (traffic), maintenance, and end-of-life
Goal definition:	To develop and apply a harmonized methodology for comprehensive LCA of freight transport services by accounting for specific system components (vehicle, fuel, infrastructure) and contextual factors (load factor, gradient, regulation), improving accuracy over standard databases
Target audience:	LCA practitioners, transport operators, infrastructure planners, policy-makers, sustainability researchers
Scoping:	Cradle-to-grave LCA for road freight transport services using a systemic traffic-centered model. Functional unit: tonne-kilometre (tkm). Includes three case studies with varying road, vehicle and fuel conditions. Uses ReCiPe midpoint and endpoint indicators (SimaPro v8.5) and detailed inventory allocation by transport component
Nature of inventory data:	High-resolution data: route segmentation by gradient/speed, vehicle age/specs, emission control tech (Euro pre–Euro VI), load factors, national Gtkm and vkm stats for infrastructure allocation, specific biofuel origin. Fuel emissions calculated with Tier 3 EMEP/EEA methodology by section; Excel tool developed for inventory estimation
Quality assessment:	Methodologically advanced and highly context-specific. Strong allocation method, scenario comparison, and normalized impact interpretation. Full alignment with ISO 14040. Limitations include exclusion of social/economic impacts and dependence on assumed allocation baselines. Superior granularity to standard datasets (e.g. EcoTransIT, Ecoinvent)
Impact assessment:	Conducted with ReCiPe midpoint indicators and normalized results. Main contributors: traffic (climate change, toxicity), fuel production (eutrophication, fossil depletion), vehicle and road manufacturing (mineral/resource depletion). Biodiesel production significantly increased impacts in Malaysia and Spain due to palm oil origin

Environmental impact categories:	• Climate change (CO_2eq) • Fossil fuel depletion • Particulate matter and NOx emissions • Terrestrial and marine ecotoxicity • Eutrophication (freshwater and marine) • Human toxicity • Land occupation and transformation • Water consumption and metal depletion
Benefit assessment methods:	No direct mitigation model. Benefits derived through improved accuracy of environmental impact allocation. Scenarios highlight need for electrification, efficient routing, and high vehicle load factors. Insights support policy design, service optimization, and future modal comparisons (e.g. electric freight)

CASE STUDY NO.75

Name:	*Determining the Environmental Potentials of Urban Pavements by Applying the Cradle-to-Cradle LCA Approach for a Road Network of a Midscale German City*
Country:	Germany (2021)
Assessed activity:	Design, construction, maintenance and recycling of flexible urban pavements
Nature of the activity:	Full cradle-to-cradle life cycle assessment of urban asphalt pavement systems
Life cycle phases:	Raw material extraction, asphalt production, transport, construction, maintenance, deconstruction, and recycling
Goal definition:	To support sustainable road network planning by evaluating the environmental performance of pavement materials, structures, and maintenance strategies using a cradle-to-cradle approach under real conditions in Münster
Target audience:	Road infrastructure managers, municipal decision-makers, environmental engineers, LCA researchers
Scoping:	Full cradle-to-cradle LCA with closed-loop recycling model of reclaimed asphalt pavement (RAP); comparison between traditional and modified pavement structures (high RAP content) under various traffic load classes and four service lifetimes (20–100 years). Functional unit: 1 m^2 of pavement
Nature of inventory data:	Primary data from local asphalt plant and municipality; Ecoinvent 3.5 used via SimaPro 9.0. Includes transport distances, machine energy consumption, maintenance frequencies, RAP processing, asphalt mix recipes. Monte Carlo simulations applied for uncertainty analysis
Quality assessment:	High methodological robustness. ISO 14040/14044 aligned, complete LCI, and sensitivity analysis performed. Monte Carlo simulations increase confidence in results. Limitations include performance assumptions (equal durability) and location-specific data. Strong for design-phase environmental decision support
Impact assessment:	Two indicators applied: non-renewable cumulative energy demand (nr-CED, MJ/m^2) and global warming potential (GWP, kg CO_2eq/m^2). Results show modified structures consistently outperform traditional ones. Production and transport phases dominate impacts (~98%). Differences amplified over time
Environmental impact categories:	• Global warming potential (CO_2eq) • Non-renewable cumulative energy demand • Indirect impacts: material sourcing, energy use, transport-related emissions • Maintenance-induced emissions • RAP benefits from reduced virgin material use and transport distances

Benefit assessment methods:	Benefits quantified via impact reduction (up to 54% nr-CED, 41% GWP). RAP integration and optimized maintenance scheduling reduce long-term impacts. Monte Carlo analysis confirms superiority of modified structures across lifetimes. Extrapolation estimates large-scale emissions and energy savings for urban road networks

CASE STUDY NO.76

Name:	*Life cycle assessment of carbon emissions for cross-sea tunnel: A case study of Shenzhen-Zhongshan Bridge and Tunnel in China*
Country:	China (2024)
Assessed activity:	Construction, operation and end-of-life of cross-sea tunnel and artificial island infrastructure
Nature of the activity:	Cradle-to-grave life cycle assessment (LCA) of carbon emissions from large-scale infrastructure
Life cycle phases:	Materialization, transportation, construction, service, end-of-life
Goal definition:	To quantify life-cycle carbon emissions of a complex cross-sea tunnel infrastructure and assess reduction potentials, using a detailed LCA model adapted to the Shenzhen-Zhongshan Bridge and Tunnel
Target audience:	Civil and environmental engineers, policymakers, infrastructure sustainability researchers, LCA practitioners
Scoping:	Full LCA with defined system boundaries, including extraction, production, transport, construction, operation, and disposal. Functional unit: per meter of tunnel. Specific to tunnel and artificial island segments. Incorporates dynamic carbon flow modelling using a social discount rate
Nature of inventory data:	Detailed material, energy, machinery and transport data from field surveys, construction documents and Gabi database. Covers steel, concrete, cement, electricity, diesel, etc. Includes maintenance and end-of-life waste flows. Adapted emission factors and transportation models used
Quality assessment:	High methodological quality. Systematic inventory collection with field, database, and literature sources. Carbon emission models built on IPCC emission coefficient methodology. Strong breakdown by phase and material. Dynamic discounting of carbon emissions during service stage included. High replicability and transparency
Impact assessment:	Carbon emissions calculated per life cycle stage: materialization (474.9 kt CO_2eq, 56%), service (248.3 kt, 29.2%), transportation (71.7 kt), end-of-life (41.9 kt), and construction (12.7 kt). Steel and cement dominate embodied emissions. Electromechanical operation and maintenance drive service stage. Recycling modeled for emission offset
Environmental impact categories:	• Carbon emissions (CO_2eq) per material and process • Embodied carbon from materials (steel, cement, concrete) • Operational energy consumption (electricity for ventilation, lighting) • End-of-life waste treatment emissions

	• Transport-related emissions (material and waste logistics)
Benefit assessment methods:	Emissions reduction potential assessed via recycling (93.5% reduction from concrete, stone, sand), renewable electricity in service phase, and optimized material use. No monetary valuation; benefits presented in CO_2eq savings per strategy and phase

CASE STUDY NO.77

Name:	*The "price" of saved time, the illusion of saved fuel: Life-Cycle Assessment of a major highway expansion*
Country:	Italy (2022)
Assessed activity:	Environmental impact evaluation of the expansion and deviation works of a mountainous section of the Italian A1 highway between Florence and Bologna
Nature of the activity:	Transport infrastructure – highway expansion project
Life cycle phases:	Construction (road base, tunnels, viaducts, furniture), operation (fuel use, maintenance), partial end-of-life (selective recycling considered for metals)
Goal definition:	To compare the environmental performance of a highway section before and after a major expansion, integrating LCA results with previous cost-benefit and emergy assessments to better inform infrastructure planning and policy
Target audience:	Transport planners, public works authorities, environmental decision-makers, sustainability scholars
Scoping:	System boundary includes construction and use phases; functional unit: annual transport service (1.28E+09 p-km and 3.34E+09 t-km); infrastructure-specific boundary spans 55 km section (Sasso Marconi–Barberino del Mugello)
Nature of inventory data:	Primary data from official records and previous studies (Cristiano & Gonella, 2019); secondary data from Ecoinvent 3.1; refined inventory includes tunnel, viaduct, asphalt layers, safety elements, and annual operational energy/fuel
Quality assessment:	High – data validated against multiple sources; impact contributors cross-checked through relative contribution graphs; sensitivity analysis performed (±20%) on tunnels, top layers, and fuel inputs

Impact assessment:	• Method: Attributional Life Cycle Assessment per ISO 14040/44
	• Software: SimaPro 9.0.0.49
	• Databases: Ecoinvent 3.1
	• Impact methods:
	  ▪ ReCiPe Midpoint v1.10 (Egalitarian) – 14 environmental indicators
	  ▪ ReCiPe Endpoint v1.10 (Egalitarian) – 5 human health indicators (DALY-based)
	  ▪ Cumulative Exergy Demand (CED) – subdivided by source (renewables/non-renewables)
	  ▪ IPCC GWP 100a for carbon footprint

Environmental impact categories:	• GWP (+169%), Ionising Radiation (+57%), PM2.5 (+179%), Eutrophication (Freshwater +214%, Marine +188%), Ecotoxicity (Terrestrial +234%, Freshwater +226%, Marine +202%)

	• Land use (+208%), Water consumption (+134%) • Fossil resource scarcity (+48%), Mineral resource scarcity (+237%) • Cumulative Exergy Demand (non-renewable metals +239%, renewables +140–244%) • Human health (DALY): GWP impact +169%, carcinogenic toxicity +235%
Benefit assessment methods:	• No monetization of environmental impacts; however, critical integration with previous cost-benefit analysis • Time savings (+) not captured in LCA, while fuel savings were neutralized by construction impacts • Net increase in all 30 impact categories after expansion; reveals hidden environmental cost of large-scale civil works • Scenario-based comparison: pre- vs. post-expansion highway section • Sensitivity analysis confirmed robustness of findings

CASE STUDY NO.78

Name:	*Life Cycle Assessment of Current Portuguese Railway and Future Decarbonization Scenarios*
Country:	Portugal (2023)
Assessed activity:	Construction, operation, and electrification upgrade of the Douro railway line
Nature of the activity:	Specific solution
Life cycle phases:	Cradle-to-use phase (construction, maintenance, and operation; end-of-life excluded)
Goal definition:	To assess the life cycle environmental impact of the conventional Portuguese railway through a case study of the Douro line, and to evaluate future decarbonization scenarios under projected electricity mixes
Target audience:	Railway infrastructure managers, sustainability researchers, transport policy-makers
Scoping:	Cradle-to-use system including materials for construction and maintenance of infrastructure and rolling stock, and operational energy consumption (diesel/electric). End-of-life stages excluded. Four scenarios: current (diesel/electric), full electrification with 2019, 2030 and 2050 electricity mixes
Nature of inventory data:	Based on sectoral LCA data (Tuchschmid et al.), primary infrastructure data from Infraestruturas de Portugal, rolling stock inventory from national reports, and electricity/diesel data modelled in SimaPro. Functional unit: 1 passenger-kilometre (pkm)
Quality assessment:	ISO 14040/44 compliant LCA. Scenario-based analysis with national infrastructure parameters and locally specific data. Robust quantification of electricity and diesel consumption. Limitations include exclusion of EoL and ancillary services (e.g. parking, brake abrasion)
Impact assessment:	Attributional LCA using ReCiPe 2016 and CED for GWP, energy use, and selected airborne pollutants. Rolling stock construction has low impact; diesel dominates GWP. Electrification yields up to 63% GHG reduction in the 2050 scenario
Environmental impact categories:	• Global Warming Potential (GWP – CO_2 eq) • Cumulative Energy Demand (CED) • Sulphur Dioxide (SO_2) emissions • Nitrogen Oxides (NO_x) emissions • Non-Methane Volatile Organic Compounds (NMVOC) • Particulate Matter (PM10)
Benefit assessment methods:	Benefits assessed through scenario-based emission reductions (e.g., 63% GHG cut by 2050); includes sensitivity analysis on passenger uptake, renewable electricity share, and infrastructure material substitutions

CASE STUDY NO.79

Name:	*Life Cycle Assessment of an Innovative Hybrid Highway Bridge Made of an Aluminum Deck and Glulam Timber Beams*
Country:	Canada (Québec) (2022)
Assessed activity:	Environmental and economic assessment of two alternative bridge deck systems: aluminum on glulam timber beams vs. aluminum on steel girders, compared to a conventional concrete/steel deck
Nature of the activity:	Transport infrastructure – highway bridge design and construction
Life cycle phases:	Design, construction, maintenance, and end-of-life (75-year analysis); operation and traffic modeled via diversion impacts
Goal definition:	To quantify life cycle costs and environmental impacts of alternative lightweight deck systems to promote sustainable bridge construction in Québec's winter climate
Target audience:	Civil engineers, public infrastructure agencies (MTQ), material developers, policy planners
Scoping:	System boundaries include the bridge superstructure (deck and beams); functional unit: 75-year service life of a 20 m span, 11.5 m wide bridge in urban context; three nested perimeters: (1) construction, (2) maintenance, (3) traffic diversion impacts
Nature of inventory data:	Design data from structural simulations and Canadian design codes (CHBDC, CSA O86), maintenance frequencies from MTQ experience, environmental data from Ecoinvent 3.3; project-specific cost and performance metrics from Québec bridge P-17683
Quality assessment:	Deterministic LCA/LCC with extensive sensitivity analysis (vehicle flow, diversion length, material origin); data reviewed and cross-referenced with prior MTQ reports; OpenLCA 1.7.2 used
Impact assessment:	• Standards: ISO 14040/44 • Tool: OpenLCA 1.7.2 • Method: IMPACT 2002+ (European midpoint and endpoint model) • Four damage categories: human health (DALY), ecosystem quality (PDF·m^2·yr), climate change (kg CO_2eq), and resource use (MJ) • Material-specific elementary flows modeled via Ecoinvent (cut-off system)
Environmental impact categories:	• Bridge construction: aluminum/wood solution had 18% lower impact than aluminum/steel across all categories

	• Full lifecycle: aluminum/wood bridge showed 85%–88% lower environmental impact vs. conventional concrete/steel bridge due to fewer maintenance needs and rapid prefabrication • Traffic diversion contributed up to 86% of total environmental impact • Recyclability of glulam beams further reduced full lifecycle impact by 24%
Benefit assessment methods:	• Life Cycle Cost (LCC) analysis used discounted cash flow (DCF) method with MTQ-recommended rates • Indirect user costs (from road closures) accounted for ~80% of total costs • Aluminum/wood bridge had 4–8% lower total cost vs. aluminum/steel bridge, and >85% cost savings vs. concrete/steel decks • Prefabrication, local sourcing, and minimal maintenance were key to both environmental and cost performance • No ecosystem service monetization included, but full cost-of-ownership model applied

CASE STUDY NO.80

Name:	*Life cycle inventory and impact assessment for an asphalt pavement road construction—a case study in Brazil*
Country:	Brazil (2021)
Assessed activity:	Environmental impact assessment of asphalt road construction using primary data from two federal highways (BR-251 and BR-356)
Nature of the activity:	Transport infrastructure – asphalt road construction
Life cycle phases:	Material extraction, transport, asphalt production, construction machinery operation (use, maintenance, and EOL excluded)
Goal definition:	To establish baseline environmental impacts for asphalt pavement construction in Brazil using primary national data, and to compare diesel vs. biodiesel use in transport
Target audience:	Environmental regulators, transport infrastructure planners, LCA practitioners in Latin America
Scoping:	Cradle-to-site boundaries including material sourcing, transport, and road layer construction; functional unit: 1 km of 2-lane road (7.2 m wide); alternative scenario uses soybean biodiesel instead of diesel for transport
Nature of inventory data:	Detailed bottom-up data from DNIT project reports; local emission factors (Ecoinvent v3.3), machinery specs (Caterpillar, VW), Brazilian diesel and biodiesel processes (Fehrenbach et al.); supplementary Excel sheet provided
Quality assessment:	High – uses two LCIA methods per category (ReCiPe 2016 and alternative: IPCC, CML, EDIP, USEtox); sensitivity analysis via method cross-checks; scenario analysis for biodiesel impact

Impact assessment:	• Standards: ISO 14044:2006
	• Software: OpenLCA 1.10.2
	• Methods:
	  ▪ ReCiPe 2016 Midpoint (H)
	  ▪ Comparison methods: IPCC (GWP), CML 2001 (TAP, ODP), EDIP 2003 (FWEP, MEP), USEtox (FWECP)

Environmental impact categories:	• GWP (Global warming potential) – transport (57.5%), gravel (16.1%) • TAP (Terrestrial acidification) – gravel (55.8%), transport (19.4%) • ODP (Ozone depletion) – pitch (56.8%), transport (30.6%) • FWEP (Freshwater eutrophication) – transport (55.4%), gravel (25.1%) • MEP (Marine eutrophication) – gravel (61.8%), machinery (13.8%) • FWECP (Freshwater ecotoxicity) – transport (51.5%), gravel (32.8%)

	• Alternative scenario using soy biodiesel increased GWP by 29%, MEP by 6.3×, FWECP by 1.7×
Benefit assessment methods:	• Comparative scenario (diesel vs. biodiesel) for transport only • No economic valuation or external co-benefit estimation included • Biodiesel increased all impacts except ODP; driven by land use and emissions in soybean cultivation • Highlights importance of material transport and production phase in early-stage mitigation planning

CASE STUDY NO.81

Name:	*Informative Study on the Integration of the Railway in Valladolid*
Country:	Spain (2021)
Assessed activity:	Railway infrastructure integration in urban setting
Nature of the activity:	Construction and modernization of railway corridor, including underground tracks and new passenger station
Life cycle phases:	Planning, construction, and operation
Goal definition:	To analyze and select the most suitable alternative for the urban integration of the railway line in Valladolid, minimizing environmental and social impacts
Target audience:	Environmental authorities, national infrastructure planners, public stakeholders
Scoping:	Focused on the 12.87 km section of the Valladolid railway corridor, involving high-speed and conventional track adaptation, urban integration, and reduction of freight traffic through the urban area
Nature of inventory data:	Based on official project documentation, technical studies, and national regulatory guidelines (Law 21/2013 and its amendments)
Quality assessment:	The study demonstrates a high level of methodological rigor, with detailed inventory data, alternative scenario evaluation, and explicit regulatory alignment. Environmental impacts are characterized using CEDEX recommendations and the Air Pollutant Emission Inventory Guidebook (EEA, 2016). The evaluation includes quantitative analysis of greenhouse gas emissions, landscape, air quality, noise, vibration, and cumulative effects. The presence of multiple scenario comparisons and explicit residual and synergistic impact considerations reflect robust quality.
Impact assessment:	Comprehensive, including climate change, air quality, noise, vibrations, land use, biodiversity (Natura 2000 network, HICs), and socio-economic effects
Environmental impact categories:	Air emissions (GHG and pollutants), noise, vibrations, land occupation, ecological fragmentation, landscape, and resource consumption
Benefit assessment methods:	Comparative analysis of alternatives, quantification of GHG emissions, qualitative and quantitative impact matrices, and cost-benefit considerations with mitigation and compensation measures

CASE STUDY NO.82

Name:	*Studio di Impatto Ambientale – Raddoppio della tratta PM228–Castelplanio (Lotto 2)*
Country:	Italy
Assessed activity:	Doubling of the railway section between PM228 and Castelplanio, as part of the Orte–Falconara infrastructure enhancement
Nature of the activity:	Major railway infrastructure development
Life cycle phases:	Planning, construction, operation
Goal definition:	To assess and mitigate the environmental impacts of the railway doubling project aimed at improving the freight and passenger transport capacity along the Adriatic-Tyrrhenian corridor
Target audience:	Ministry of Ecological Transition, RFI, regional and municipal authorities, stakeholders involved in railway and environmental planning
Scoping:	Not a formal LCA. Complies with Italian Legislative Decree 152/2006 and EU EIA Directive 2014/52/EU. Includes alternative scenarios, full baseline environmental inventory, multi-criteria evaluation, and impact matrices. Project aligned with PNRR and Green Deal transport objectives
Nature of inventory data:	Includes noise/vibration models, CO_2eq reduction projections, air and water quality data, flora-fauna surveys, land use mapping, and health indicators. Calculations supported by ISPRA emission factors and national vehicle fleet projections. No material or energy flow inventory in LCA format
Quality assessment:	Technically comprehensive and compliant with legal EIA structure. Incorporates climate change mitigation, GIS mapping, emissions balance, risk assessments, and habitat characterizations. Not an LCA; does not use functional units or standardized impact categories, but provides robust environmental and energetic projections
Impact assessment:	Conducted through sector-specific chapters (soil, air, water, biodiversity, noise, climate, health, landscape, heritage). Includes both construction and operational phases. Quantitative estimation of avoided CO_2eq emissions (246,777 t by 2050), PM, NOx, NMVOC, SO_2 and Pb reductions, and energy savings (2,463 TEP) from modal shift
Environmental impact categories:	• GHG emissions and climate change mitigation • Air pollutants (PM2.5, NOx, NMVOC, SO_2, Pb) • Biodiversity impacts (habitat disturbance, fragmentation) • Landscape transformation • Noise, vibration, and water quality alteration
Benefit assessment methods:	Quantified via modal shift modelling (private to rail), transport energy simulations, and emission avoidance based on national fleet evolution scenarios. Long-term energy and climate savings considered. Includes additional qualitative co-benefits (accessibility, modal integration)

CASE STUDY NO.83

Name:	*Life Cycle Assessment as Decision-Support in Choice of Road Corridor: Case Study and Stakeholder Perspectives*
Country:	Sweden (2021)
Assessed activity:	Evaluation of environmental performance of alternative road corridor options using LCA and stakeholder feedback on the LICCER model
Nature of the activity:	Infrastructure planning – road corridor selection (strategic-level decision support)
Life cycle phases:	Material production, construction, operation, end-of-life, and traffic operation (cradle-to-grave)
Goal definition:	To explore how the LICCER model supports early-stage planning of road infrastructure by quantifying climate impact and energy use, and to assess its usefulness through stakeholder engagement
Target audience:	Road authorities, infrastructure planners, LCA practitioners, transport policy developers
Scoping:	Functional unit: "Road infrastructure enabling annual traffic between points A and B over a defined number of years" (20 years used); system boundaries cover infrastructure and traffic; applied to three alternatives and one reference (existing) road section in Sweden
Nature of inventory data:	Combination of project-specific data (from feasibility study and traffic forecasts) and default values from the LICCER model; estimates based on prior construction projects and national databases
Quality assessment:	Model transparency and stakeholder review ensure robustness; sensitivity analysis performed (10% variation in key parameters); does not rely on proprietary LCI databases (e.g., Ecoinvent); data adapted for Swedish/Nordic context
Impact assessment:	• Tool: LICCER model (Excel-based) • Method: Attributional LCA compliant with ISO 14040/44 • Impact indicators: ▪ Global Warming Potential (GWP100) – kg CO_2 eq ▪ Cumulative Energy Demand (CED) – MJ (includes feedstock energy) ▪ Disaggregated impacts by: life cycle stage, material, vehicle type, and traffic scenario ▪ No midpoint-to-endpoint conversion; results interpreted at midpoint level

Environmental impact categories:	• GHG emissions from infrastructure (materials, construction, resurfacing, EOL) • GHG emissions from traffic (operation of different vehicle types and fuel mixes) • Energy use (production + operational stages) • Traffic emissions dominate (>90%) across all corridors; infrastructure variation driven by asphalt, earthworks, and soil stabilization
Benefit assessment methods:	• LICCER model includes results visualization relative to reference, helping identify "hotspot" materials and stages • No monetary or ecosystem service valuation included

CASE STUDY NO.84

Name:	*Environmental Impact Assessment of the Electrification of the Bobadilla–Ronda Railway Line*
Country:	Spain (2021)
Assessed activity:	Electrification of a 73.6 km segment of the Bobadilla–Algeciras railway line, including construction of overhead catenary systems, substations, and associated infrastructure
Nature of the activity:	Transport infrastructure – railway electrification project
Life cycle phases:	Design, construction (catenary, substations, access roads), and operation; end-of-life not considered
Goal definition:	To assess the environmental impacts of different electrification layout alternatives to ensure legal compliance and minimize environmental harm in a Natura 2000 zone
Target audience:	Ministry for the Ecological Transition and Demographic Challenge (Spain), ADIF, regional environmental authorities, infrastructure planners
Scoping:	• Three design alternatives + baseline (no action) • System boundary includes construction of overhead electrification (catenary, supports, transformer stations), access roads, and minor structural adjustments (e.g., viaduct footings) • Focused on direct environmental interactions during construction and long-term operation (e.g., emissions, land take, biodiversity)
Nature of inventory data:	• Primary engineering data from ADIF and contractors • Environmental baseline from field studies (flora, fauna, geology, water) • Waste estimation using regional construction waste guides (Catalonia's 2014 decree and ITEC methodology)
Quality assessment:	• Legal and technical compliance with Law 21/2013 on Environmental Assessment • Alternatives analysis using multi-criteria evaluation with indicators normalized on a 0–10 scale • Weighting and sensitivity analysis applied to environmental, functional, and cost criteria
Impact assessment:	• Matrix-based evaluation for construction and operation phases • Impact significance scored by magnitude and duration • Categories include air, soil, water, biodiversity, landscape, cultural heritage, and human health

	• No formal LCA or impact modeling software used; qualitative and semi-quantitative methodology adopted
Environmental impact categories:	• Land take and habitat fragmentation (notably near Lagunas de Campillos, a Ramsar site and ZEC/ZEPA) • Air emissions during construction (diesel machinery, dust) • Acoustic pollution (especially nighttime train noise near residences) • Waste generation: construction debris, used oils, and SF_6 from transformers • Electromagnetic fields from new substations (assessed separately) • Water quality and runoff risks (especially near drainage works and flood-prone areas)
Benefit assessment methods:	• Qualitative comparison of social and environmental benefits • Alternative 3 optimized to avoid critical biodiversity hotspots and cultural heritage zones • Multicriteria analysis ranks alternatives based on environmental, technical, territorial, and economic indicators • No economic valuation or carbon footprint quantification included

CASE STUDY NO.85

Name:	*Life Cycle Assessment of High-Performance Railway Infrastructure: Analysis of Superstructures in Tunnels and on Open Tracks*
Country:	Austria (2023)
Assessed activity:	Environmental assessment of ballasted vs. slab track railway superstructures using LCA for open track and tunnel sections of the Brenner Base Tunnel corridor
Nature of the activity:	Transport infrastructure – railway superstructure design
Life cycle phases:	Full cradle-to-cradle scope: raw material extraction, production, transport, construction, use (maintenance and renewal), and end-of-life (A1–C4)
Goal definition:	To quantify and compare the environmental performance of typical Austrian track systems (ballasted and slab track) across different lifespans and contexts, identifying ecological optimization potentials
Target audience:	Railway engineers, infrastructure planners (ÖBB, BBT-SE), environmental analysts, policymakers in sustainable transport
Scoping:	• Functional unit: 1 km of single-track high-performance railway infrastructure • Simulation periods: 80 and 200 years • Includes production, installation, and maintenance; excludes train operations (B1, B6–B8) • Applied to the Austrian segment of the Brenner Base Tunnel and corridor
Nature of inventory data:	• Manufacturer data, Austrian-specific railway specifications (ÖBB), technical literature, and ecoinvent v3.8 • Transport distances specified for all components; mostly electric rail transport assumed • LCI developed using SimaPro 9.3.0.3
Quality assessment:	• High: based on real Austrian practices and manufacturing • Maintenance and replacement modeled with minimum/maximum lifetime scenarios • Reuse rates (e.g., 40% concrete, 50% rails, 30% ballast) considered • Closed-loop recycling assumed where applicable
Impact assessment:	• Standards: ISO 14040, ISO 14044, EN 15804+A2 • Method: Attributional LCA • Software: SimaPro 9.3 • Sensitivity analysis for service life variation (min/max scenarios), tunnel vs. open track context

Environmental impact categories:	• Global Warming Potential (GWP, kg CO_2 eq) • Acidification Potential (AP, mol H^+ eq) • Non-renewable Cumulative Energy Demand (nrCED, MJ)
Benefit assessment methods:	• Comparative scenario modeling of ballasted vs. slab track under 80 and 200-year simulations • No monetary or endpoint valuation; benefit analysis based on net GWP/AP/nrCED tradeoffs • Optimization potential identified in rail steel and concrete composition

CASE STUDY NO.86

Name:	*Environmental Impact Assessment of the Railway Line Duplication: Montcada Bifurcació – Puigcerdà Frontera Francesa, Section Vic–Centelles*
Country:	Spain (2024)
Assessed activity:	Duplication of a single-track section (Vic–Centelles) on the R3 commuter railway line to improve service frequency and capacity
Nature of the activity:	Transport infrastructure – rail network enhancement (public service corridor)
Life cycle phases:	Design, construction, and operation phases are detailed; end-of-life not addressed explicitly
Goal definition:	To ensure compliance with Spanish EIA regulations for large railway infrastructure projects and to evaluate environmental implications of the two alignment alternatives proposed
Target audience:	Spanish Ministry of Transport, mobility planners, environmental authorities, and local municipalities
Scoping:	• Alternatives: 2 route options plus "do nothing" baseline • System boundaries: railway corridor (tracks, stations, viaducts, crossings), earthworks, auxiliary works, material transport • Functional scope: 11.5 km stretch of duplicated track, 3 stations, viaducts, underpasses, and landscape integration
Nature of inventory data:	• Primary design data (from ADIF and SAITEC) • Topographic, geological, hydrological, biological, and socioeconomic baseline field studies • Soil balance calculations (cut/fill), waste projections, material use estimates
Quality assessment:	• Methodologically aligned with Spanish Law 21/2013 on Environmental Assessment • Matrix-based impact identification and multi-criteria analysis for alternative evaluation • Uses GIS layers, species inventories, and infrastructure modeling for impact characterization
Impact assessment:	• Qualitative and semi-quantitative EIA methodology • Impact matrix: based on magnitude, duration, reversibility, and affected area • Alternative evaluation includes functional, environmental, and economic indicators (scored 0–10)

Environmental impact categories:	• Biodiversity (flora, fauna, habitats of community interest) • Water: hydrology, hydrogeology, flood risk • Soil and geology (land take, erosion risk) • Landscape and visual integration • Cultural heritage (proximity to protected sites) • Noise and vibration (especially near stations and tunnels) • Air quality (dust and emissions during construction) • Waste generation and management (spoil, construction waste)
Benefit assessment methods:	• Improved reliability and frequency of train services (25% more daily trains) • Reduced delays and increased punctuality due to double-tracking • Socioeconomic uplift in served municipalities (employment, access) • Climate mitigation co-benefits (modal shift, electrification compatibility) • No quantitative LCA or monetary valuation of environmental benefits included

CASE STUDY NO.87

Name:	*Environmental and Social Impact Assessment for the Uvinza–Kigadye Standard Gauge Railway (SGR)*
Country:	Tanzania (2023)
Assessed activity:	Construction of a 156.4 km electrified standard gauge railway linking Uvinza (Tanzania) to Kigadye (near the Burundi border)
Nature of the activity:	Public infrastructure – regional transport corridor and freight/passenger rail link
Life cycle phases:	Design, construction, operation; decommissioning included in framework (though less detailed); end-of-life not fully assessed
Goal definition:	To provide environmentally and socially responsible planning for a major railway corridor supporting international trade, regional integration, and mining logistics
Target audience:	Tanzanian Railways Corporation (TRC), NEMC, AfDB, regional planning authorities, local communities
Scoping:	• Project scope includes railway corridor, stations, access roads, substations, quarries, borrow pits, and utilities • System boundaries cover entire project lifecycle in Tanzania (not Burundi), including direct and indirect impacts • Functional system area: 156.4 km railway + station infrastructure + environmental/social buffer zones (AoI extended to >5 km where needed)
Nature of inventory data:	• Multi-disciplinary fieldwork (ecological, hydrological, social, noise, air) • Government census data (2022), TRC technical reports, field surveys, stakeholder consultations, GIS mapping • Quantitative data on land take (3,495 acres), displaced households (265 structures), and crops/trees lost
Quality assessment:	• Regulatory compliance with Tanzania EMA 2004 and EIA Regulations 2018 • Aligns with AfDB Operational Safeguards (1–5) • Alternatives analyzed (3 route options); stakeholder input integrated • Cumulative, transboundary, and climate impacts addressed
Impact assessment:	• ESIA per Tanzanian legal framework + AfDB Integrated Safeguards System • Qualitative and semi-quantitative matrix approach for biophysical and socio-economic impacts • Duration, reversibility, magnitude, and significance assessed • No formal LCA (ISO 14040/44) nor numeric environmental modeling included

Environmental impact categories:	• Land use change and habitat fragmentation • Impacts on water resources (hydrology, irrigation conflicts) • Air quality (construction dust, vehicle emissions) • Noise and vibration (construction and future operations) • Soil erosion, slope instability, waste generation • Climate risk exposure and GHG reduction potential through modal shift • Socioeconomic displacement, community health/safety, infrastructure impacts
Benefit assessment methods:	• Employment creation (short and long-term) • Regional trade facilitation (access to Burundi, DRC) • Transport efficiency and safety improvements • Local economy stimulation (agriculture, mining logistics, services) • Qualitative cost-benefit assessment included in Chapter 11; no monetary valuation of environmental externalities or LCA-based emissions offset quantified • Recommendations include gender and vulnerable group integration, grievance redress mechanisms, and institutional strengthening

CASE STUDY NO.88

Name:	*Environmental Impact Assessment of Flora and its Role in Offsetting Carbon along National Highway-16*
Country:	India (2024)
Assessed activity:	Evaluation of carbon sequestration by roadside flora on a highway upgraded from 4 to 6 lanes
Nature of the activity:	Specific solution – environmental monitoring study focused on vegetative carbon storage linked to a transport infrastructure upgrade
Life cycle phases:	Operation phase (focus on vegetative growth along existing infrastructure); indirect references to design (alignment) and impact monitoring post-construction
Goal definition:	To quantify above- and below-ground carbon stock and sequestration potential of trees planted and naturally occurring along NH-16
Target audience:	Environmental scientists, road planners, forestry departments, climate mitigation analysts
Scoping:	• System boundaries include both sides of a 193 km stretch of NH-16 (Ranasthalam to Ichapuram) • Includes all trees with DBH ≥ 30 cm within 1930 sampling plots (2×100 m each), covering 95.38 acres • Focus on living biomass (trees), excludes emissions from construction/transport or non-vegetative environmental impacts
Nature of inventory data:	• Extensive field-based inventory (1930 quadrats; 643,848 trees) • Measurement of DBH, height, canopy width, species identification • Uses GPS and allometric equations from published sources
Quality assessment:	• Ground-truthed plot-level sampling in a crisscross method • SPSS used for data analysi • Allometric models validated by literature; consistent measurement standards applied
Impact assessment:	• Biomass and carbon stock estimation via allometric equations • Carbon to CO_2 conversion using standard formulas • AGB and BGB calculated separately • No LCA, ISO standards, or broader emissions inventory tools applied
Environmental impact categories:	• Carbon sequestration (C-stock and CO_2 captured) • Tree species diversity and structural composition • Air pollution mitigation (contextual, not quantitatively assessed)

Benefit assessment methods:	• Assessment of carbon compensation capacity (total and per tree) • Sequestration potential used to infer role in offsetting CO_2 emissions from nearby traffic • Qualitative discussion on ecosystem services (biodiversity, microclimate, air quality improvement) • No monetization or formal baseline comparison included

CASE STUDY NO.89

Name:	*Post-assessment of the eco-environmental impact of highway construction – A case study of Changbai Mountain Ring Road*
Country:	China (2022)
Assessed activity:	Impact of highway construction and operation on ecosystems in a temperate forest region
Nature of the activity:	Transport
Life cycle phases:	Operation and maintenance (10-year post-construction phase)
Goal definition:	To develop a comprehensive methodology for post-assessment of eco-environmental impacts of highway projects, focusing on long-term, cumulative, and species-level effects in a forest ecosystem
Target audience:	Scientists, policymakers, environmental managers, infrastructure developers, ecological engineers
Scoping:	Examines ecological impacts of a forest highway, assessing wildlife mortality, habitat fragmentation, landscape pattern changes, vegetation recovery, and ecosystem functionality over time and space (4–7 years post-operation and within 200–300 m of the road)
Nature of inventory data:	Field data on wildlife traces, deaths, road crossings, and species distribution (2010–2016) Remote sensing imagery (2006–2016) for land use and landscape analysis Expert surveys for analytic hierarchy process weighting
Quality assessment:	• Use of Analytic Hierarchy Process (AHP) for weighting indicators • Multi-index quantitative analysis: landscape metrics (e.g., fragmentation, diversity), NDVI trends, road mortality rates • Spatial analysis using ArcGIS and Fragstats software
Impact assessment:	Methodologies used for impact quantification: • Analytic Hierarchy Process (AHP) • Landscape ecological indicators • Remote sensing (NDVI) • GIS-based buffer analysis
Environmental impact categories:	• Biodiversity (wildlife mortality, habitat connectivity, species richness) • Land use change • Landscape fragmentation and heterogeneity • Ecological function (NDVI, habitat maintenance capacity)
Benefit assessment methods:	• No direct quantification of environmental benefits • Discusses ecological stabilization and vegetation recovery over time as indicators of reduced negative impacts • Evaluation of animal passage effectiveness as potential mitigation benefits

CASE STUDY NO.90

Name:	*Life cycle environmental assessment of state and national highways in India: Evaluating impact reduction potential of sustainable measures*
Country:	India (2025)
Assessed activity:	Life cycle environmental impacts of State and National Highways with evaluation of sustainable improvement measures
Nature of the activity:	Transport infrastructure (road construction and operation)
Life cycle phases:	Material extraction, construction, use, and end-of-life of road infrastructure
Goal definition:	To evaluate environmental impacts across the entire life cycle of highway pavements in India and assess the potential of sustainable interventions for impact reduction
Target audience:	Scientists, policymakers, infrastructure planners, environmental engineers, sustainability analysts
Scoping:	Comprehensive LCA of Indian road infrastructure (State and National Highways) including flexible and rigid pavements, with assessment of improvement scenarios such as steel slag use, alternative cements, solar-powered infrastructure, EVs, hydrogen vehicles, and tree plantations
Nature of inventory data:	Primary data from site surveys, detailed project reports (DPRs), contractor interviews; secondary data from LCA for Experts (India-specific datasets)
Quality assessment:	ISO-compliant LCA methodology (ISO 14040, 14044, 21931-2); sensitivity analysis and multiple improvement scenarios evaluated with LCA for Experts 10.8 software; impact categories assessed using CML method
Impact assessment:	Methodologies used for impact quantification: Life Cycle Assessment (LCA), mid-point impact assessment (CML method), LCA for Experts software
Environmental impact categories:	• Abiotic Depletion (fossil) • Acidification Potential (AP) • Global Warming Potential (GWP) • Human Toxicity Potential (HTP)
Benefit assessment methods:	• Multiple improvement scenarios evaluated: • Construction phase: steel slag as aggregate substitute, use of Portland Slag Cement • Use phase: solar streetlighting, fuel blending (bioethanol), increased vehicle efficiency, solar panels on medians, green highways (tree plantations), electric vehicles (EVs), hydrogen vehicles (PEMWE-based hydrogen production) ▪ Carbon sequestration by roadside tree planting quantified using allometric equations ▪ Benefits assessed through comparative LCA modeling and sensitivity analysis

CASE STUDY NO.91

Name:	*Highway Ecological Environmental Assessment Based on Modified Remote Sensing Index—Taking the Lhasa–Nyingchi Motorway as an Example*
Country:	China (2024)
Assessed activity:	Evaluation of ecological impacts of a major highway (Lhasa–Nyingchi Motorway) on surrounding natural ecosystems using satellite-based remote sensing indices
Nature of the activity:	Transport infrastructure development
Life cycle phases:	Construction, operation, and ecological restoration phases of the motorway
Goal definition:	To monitor and evaluate changes in ecological environmental quality over time (2012–2020) due to the construction and use of a highway, and to validate the effectiveness of ecological restoration strategies
Target audience:	Scientists, environmental planners, policymakers, transportation authorities, and ecological restoration practitioners
Scoping:	Focused on a 5 km buffer zone on both sides of the Nyingchi to Gongbo'gyamda section of the Lhasa–Nyingchi Motorway in the fragile ecological region of Xizang (Tibet). It analyzes vegetation, heat, and moisture dynamics in relation to the road using satellite imagery over 9 years.
Nature of inventory data:	Remote sensing data from MODIS (NDVI, LAI, GPP, LST, and Wet indices) collected and analyzed using the Google Earth Engine platform. Additional geospatial and statistical processing was applied.
Quality assessment:	The study applies Principal Component Analysis (PCA) and Analytic Hierarchy Process (AHP) for weighting indicators, followed by a game theory-based combination weighting method. It also uses time-series MRSEI computation, transition matrix analysis, and spatial distribution mapping to assess changes.
Impact assessment:	Methodologies used for impact quantification: Modified Remote Sensing Ecological Index (MRSEI), PCA, AHP, combination weighting via game theory, time-series spatial analysis, transition matrices
Environmental impact categories:	• Biodiversity (via vegetation indices such as NDVI, LAI, and GPP) • Land surface temperature (thermal pollution/climate effects) • Soil and moisture degradation (via wetness index) • Land use and ecological restoration outcomes
Benefit assessment methods:	• The study quantitatively measures environmental restoration benefits post-construction using year-by-year MRSEI values and spatial categorization into ecological quality classes (poor to excellent) • Benefits are further evaluated using transition matrices to detect improvements versus degradations across ecological quality levels

CASE STUDY NO.92

Name:	*Construction Simulation and Environmental Impact Analysis: Towards a 4D-Based Analysis of Road Project Variants*
Country:	Canada (2023)
Assessed activity:	Assessment of road infrastructure project variants through 4D Building Information Modeling (BIM) to understand and visualize environmental impacts
Nature of the activity:	Transport (road construction and improvement)
Life cycle phases:	Design, construction, and operation of road infrastructure
Goal definition:	To develop and test a structured conceptual framework using 4D simulation (time-integrated 3D models) for the environmental impact assessment of different road construction project variants
Target audience:	Environmental planners, policymakers, infrastructure project designers, road engineers, BIM specialists
Scoping:	Focuses on addressing the limitations of traditional 2D environmental assessments in road projects by integrating spatio-temporal visualization techniques for better planning, communication, and decision-making. Emphasis is placed on identifying sensitive environmental receptors and simulating the evolution of impacts over time.
Nature of inventory data:	Case study-based with data derived from a real road project in northwestern Quebec, using design documents, GIS/geographic data, construction schedules, and environmental impact reports. The study uses software tools such as Infraworks, Civil 3D, Oracle Primavera, and Navisworks for 3D/4D modeling and simulation.
Quality assessment:	The methodology includes a proof of concept, structured framework testing, and validation through a real-world case. The assessment incorporates qualitative performance metrics like stakeholder comprehension, scenario clarity, model interactivity, and simulation accuracy.
Impact assessment:	• Environmental Impact Assessment (EIA) • 4D Building Information Modeling (BIM) simulation • Multi-criteria analysis (non-numerical but scenario-based) • GIS-based spatial analysis • Visualization techniques for spatio-temporal impact modeling
Environmental impact categories:	• Land use (deforestation, encroachment on habitats and wetlands) • Biodiversity (impacts on wildlife corridors and habitats) • Air quality (dust from construction) • Noise pollution (impact on residential areas)

	• Traffic disruption and safety (during construction and operation) • Visual and cumulative impacts (interaction with industrial sites, other infrastructure)
Benefit assessment methods:	• The study qualitatively discusses potential benefits in project planning, stakeholder engagement, and environmental mitigation. • Visualization-based assessments help communicate impacts clearly to non-expert stakeholders, facilitating social acceptability. • No direct quantitative benefit analysis is conducted, but 4D simulation is shown to improve decision-making and reduce the need for redundant documentation through efficient scenario analysis.

CASE STUDY NO.93

Name:	*Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis*
Country:	Switzerland (2022)
Assessed activity:	Environmental impacts of large-scale hydrogen production (500 Mt/year) via grey, blue (SMR with CCS), and green (electrolysis powered by wind or solar PV) hydrogen technologies
Nature of the activity:	Energy production
Life cycle phases:	Entire life cycle of hydrogen production excluding end-of-life; includes construction, operation, and upstream supply chains, with projections for 2020, 2035, and 2050
Goal definition:	To assess and contextualize the absolute environmental sustainability of large-scale hydrogen production technologies, using prospective life cycle assessment (pLCA) and multiple impact assessment and normalization methods
Target audience:	Scientists, policymakers, energy planners, environmental analysts, and sustainability assessment professionals
Scoping:	Global-scale assessment of future hydrogen production scenarios (2050), evaluating their transgressions against Planetary Boundaries, human health, and environmental impacts, and considering system-wide technological and supply chain changes
Nature of inventory data:	Prospective life cycle inventories generated using the premise tool based on ecoinvent 3.8, integrated with IAM projections (REMIND model, SSP2, RCP2.6). Includes updated data for 2020, 2035, and 2050 for each hydrogen technology route.
Quality assessment:	Comprehensive sensitivity analysis for key parameters (e.g., carbon capture rate, electrolyzer efficiency); implementation of four LCIA methods; normalization to global economy benchmarks (years 2000 and 2010); consistent comparison across different technologies and years using harmonized system boundaries
Impact assessment:	Methodologies used for impact quantification: • Prospective Life Cycle Assessment (pLCA) following ISO 14040 • Planetary Boundaries–based Life Cycle Impact Assessment (PB-LCIA) • ReCiPe 2016 Midpoint (H) • Environmental Footprint 3.0 (Midpoint) • CML-IA baseline 4.8 (Midpoint) • Monetization of environmental externalities (ReCiPe & CML)

	• DALY (Disability-Adjusted Life Years) conversion for health impacts
Environmental impact categories:	• Climate change (GWP) • Human toxicity (carcinogenic and non-carcinogenic) • Marine and freshwater ecotoxicity • Resource depletion (fossil and mineral) • Particulate matter formation • Photochemical ozone formation • Eutrophication (marine and freshwater) • Land use • Biodiversity loss (biosphere integrity) • Biogeochemical flows (e.g., nitrogen into water)
Benefit assessment methods:	• Monetization of environmental externalities to derive full-cost accounting of hydrogen production • DALYs compared to global disease burdens to assess scale of human health impacts • Mitigation cost analysis (USD per ton of CO_2 avoided vs natural gas baseline) • Normalization of impacts relative to historical global economic impact profiles • Sensitivity analysis to identify potential co-benefits (e.g., lower health impacts from wind-based green H_2 due to lower particulate emissions)

CASE STUDY NO.94

Name:	*Environmental impact and damage assessment of the natural gas pipeline: Case study of Iran*
Country:	Iran (2022)
Assessed activity:	Environmental impacts of the operation of a section of the sixth national gas trunkline transporting natural gas across southwestern to northwestern Iran
Nature of the activity:	Energy transport infrastructure (natural gas pipeline)
Life cycle phases:	Operation phase (transport of natural gas via pressure boosting stations)
Goal definition:	Evaluating and quantifying environmental impacts (emissions to air, water, and soil) and ecological/human health damage associated with the operation of gas compressor stations in the pipeline
Target audience:	Environmental scientists, energy policymakers, infrastructure planners, environmental regulators
Scoping:	Focuses on five pressure boosting stations in Iran's sixth national gas pipeline. The system boundary includes only the transfer stage (from gas refinery to border/export points), excluding upstream extraction and downstream consumption phases. The functional unit is defined as 1 cubic meter of transported gas.
Nature of inventory data:	Field data collected for 2019 for each station, including gas input/output flows, gas leakage, turbine emissions (NOx, CO, etc.), electricity and fuel consumption, black powder composition, and pollutant release measurements.
Quality assessment:	Analysis conducted using SimaPro software (ISO 14040/44 compliant), applying the ReCiPe 2016 method (Midpoint and Endpoint perspectives). Includes sensitivity analysis with Monte Carlo simulation to evaluate uncertainty in emissions results.
Impact assessment:	Methodologies used for impact quantification: Life Cycle Assessment (LCA) using ReCiPe 2016 (Midpoint and Endpoint methods)
Environmental impact categories:	• Global warming (kg CO_2 eq) • Stratospheric ozone depletion (kg CFC-11 eq) • Ionizing radiation (kg Co-60 eq) • Ozone formation (kg NOx eq) • Fine particulate matter formation (kg PM2.5 eq) • Acidification potential (kg SO_2 eq) • Freshwater and marine eutrophication (kg P eq / kg N eq) • Ecotoxicity (freshwater, marine, terrestrial; kg 1,4-DCB eq)

	• Human toxicity (carcinogenic and non-carcinogenic) • Land use (m^2a crop eq) • Resource scarcity (mineral and fossil, kg Cu eq) • Water consumption (m^3)
Benefit assessment methods:	The study does not quantify environmental benefits; it is focused exclusively on assessing and comparing negative environmental impacts and damage potentials across stations. However, the conclusion suggests the potential for future mitigation through optimization of station operations.

CASE STUDY NO.95

Name:	*Environmental benefit analysis of "road-to-rail" policy in China based on a railway tunnel measurement*
Country:	China (2021)
Assessed activity:	Substitution of long-distance road freight transportation with railway (diesel and electric locomotives) and its effect on air pollution and energy use
Nature of the activity:	Transport
Life cycle phases:	Operation of transport infrastructure and vehicles, including upstream (fuel production) and downstream (vehicle emissions) phases
Goal definition:	To quantify real-world emission factors of diesel locomotives in China and evaluate the environmental benefits of the "road-to-rail" modal shift using life cycle analysis
Target audience:	Scientists, transport policymakers, environmental regulators, infrastructure planners
Scoping:	Evaluates emissions from 245 in-use diesel locomotives using tunnel-based real-world measurements and compares road-to-rail shift scenarios using life cycle assessment; includes policy scenarios, modal shift ratios, and electrification levels
Nature of inventory data:	Empirical emission data collected through tunnel measurements (Wangzhuang Tunnel, Beijing); scenario modeling using transportation statistics and GREET model data
Quality assessment:	Statistical methods include reduced major axis (RMA) regression, scenario analysis, comparative evaluation against national inventory data and standards (e.g., Tier 2, China VI), and uncertainty analysis through emission factor ranges
Impact assessment:	Methodologies used for impact quantification: Life Cycle Assessment (LCA); fuel life cycle analysis (Well-to-Wheel, including Well-to-Tank and Tank-to-Wheel stages); GREET model for upstream emissions
Environmental impact categories:	Air pollutants (NOx, CO, SO_2, black carbon), energy consumption (MJ), transportation-specific emissions, and exposure risk
Benefit assessment methods:	• Benefits assessed via comparative emission reduction across scenarios (e.g., 100% diesel locomotives, 20% diesel + 80% electric, 100% electric) • Modeled reductions in NOx and BC emissions under real and idealized emission factor assumptions • Analysis includes time-series projections on emission reduction sustainability (short vs. long term), as well as recommendations for electrification acceleration and diesel emission control policies

CASE STUDY NO.96

Name:	*Environmental performance analysis of railway infrastructure using life cycle assessment: Selecting pavement projects based on global warming potential impacts*
Country:	Brazil (2022)
Assessed activity:	Evaluation of different sub-ballast materials in freight railway infrastructure and their impact on global warming potential
Nature of the activity:	Transport
Life cycle phases:	Extraction of materials, construction, operation, maintenance, and renewal of rail freight infrastructure over a 200-year period
Goal definition:	To identify main contributors to global warming potential from rail freight transport infrastructure and support the selection of pavement solutions based on environmental performance
Target audience:	Infrastructure investors, railway engineers, environmental managers, policymakers
Scoping:	Focuses on the LCA of 1 km of Brazilian freight railway track with various sub-ballast materials (sandy soil, soil-cement, soil-emulsion, and HMA), and under different subgrade moisture conditions. Excludes rolling stock, signaling, drainage, tunnels, and bridges
Nature of inventory data:	Based on field measurements, national construction databases (SICRO), lab tests, Ecoinvent v3.6 datasets in SimaPro 9.3. Inventories include construction materials, equipment, transport, and energy consumption
Quality assessment:	Applies mechanistic-empirical models for structural lifespan estimation, finite element modeling for stress-strain analysis, and LCA methodology following ISO 14040 standards using CML-IA baseline and EU25 normalization. Comparative analysis across eight scenarios
Impact assessment:	Methodologies used for impact quantification: Life Cycle Assessment (LCA) using SimaPro 9.3, with EcoInvent v3.6 database
Environmental impact categories:	Global warming potential (GWP) quantified in gCO_2eq/km/year
Benefit assessment methods:	The study does not quantify direct environmental "benefits" but evaluates trade-offs between infrastructure lifespan and emissions across materials and conditions, offering decision-support for minimizing GWP in rail infrastructure planning

CASE STUDY NO.97

Name:	*Exploring non-linear built environment effects on the integration of free-floating bike-share and urban rail transport: A quantile regression approach*
Country:	China (2022)
Assessed activity:	Integration of free-floating bike-sharing (FFBS) with urban rail transport (URT) in Nanjing, assessing the effects of the built environment
Nature of the activity:	Transport
Life cycle phases:	Operation phase of urban mobility systems (bike-sharing and rail transport infrastructure)
Goal definition:	To examine the nonlinear effects of built environment characteristics on the integration of FFBS with URT across different usage levels and time periods
Target audience:	Urban planners, transport operators, policymakers, academics in urban mobility and transport planning
Scoping:	The study investigates spatial and temporal dynamics of FFBS-URT integration, focusing on how built environment variables (e.g., population/employment density, road network, parking infrastructure) affect usage levels differently depending on quantiles of integrated use
Nature of inventory data:	• Trip data from Mobike (3.12 million trips over 5 weekdays) in Nanjing • Built environment data from the Nanjing Urban GIS database • Analysis based on 800m catchment zones around 129 urban rail stations
Quality assessment:	• Quantile regression modeling applied at multiple quantiles (5th to 95th) • Robust standard errors clustered at station level • Descriptive statistics and correlation diagnostics included
Impact assessment:	• Methodologies used for impact quantification: Quantile regression (econometric/statistical modeling approach)
Environmental impact categories:	• Modal shift (e.g., from cars to bikes/public transport) • Accessibility and land use efficiency • Urban sustainability • Potential GHG reduction (cited from secondary literature but not directly assessed in this study)
Benefit assessment methods:	• Environmental and transport system benefits are discussed qualitatively and supported by literature (e.g., reduced GHG emissions, improved multimodal accessibility) • No explicit quantification of environmental benefits within the core study, but referenced from scenario modeling in external studies (e.g., GHG savings in New Delhi)

CASE STUDY NO.98

Name:	*Assessing carbon dioxide emissions of high-speed rail: The case of Beijing–Shanghai corridor*
Country:	China (2021)
Assessed activity:	Carbon dioxide emissions of high-speed rail (HSR) in the Beijing–Shanghai corridor, considering mode substitution and traffic generation
Nature of the activity:	Transport
Life cycle phases:	Infrastructure construction, rolling stock manufacturing, and operation of the high-speed rail line
Goal definition:	To conduct an ex-post life-cycle assessment of net CO_2 emissions of the Beijing–Shanghai HSR by accounting for mode substitution effects (from road, air, and ordinary-speed rail) and traffic generation
Target audience:	Scientists, transport planners, infrastructure investors, environmental policymakers
Scoping:	Assesses environmental impact of a long-distance HSR line using real operational and traffic data. Evaluates the emissions consequences of shifting traffic from other transport modes (air, road, ordinary-speed rail) and generating new demand. Avoided infrastructure expansion and vehicle manufacturing in other modes are also considered.
Nature of inventory data:	• Empirical traffic data from 2011–2017 for HSR, expressway, OSR, and air routes • Energy consumption data • CO_2 emission factors for infrastructure components and electricity generation • Life-span and technical specifications for different transport modes
Quality assessment:	• Quantitative life-cycle approach based on real-world (ex-post) data • Use of counterfactual scenarios (with vs. without HSR) • Emission factors sourced from established literature (e.g., Baron et al., 2011) • Includes validation against actual infrastructure and traffic development
Impact assessment:	Methodologies used for impact quantification: Life Cycle Assessment (LCA), counterfactual emissions modeling
Environmental impact categories:	Carbon dioxide emissions (CO_2), energy consumption (implied through CO_2 conversion)
Benefit assessment methods:	• The study quantifies avoided CO_2 emissions from reduced vehicle manufacturing and infrastructure construction due to modal shift • Benefits assessed through comparison of actual emissions with a no-HSR baseline scenario over infrastructure life cycles

CASE STUDY NO.99

Name:	*Sustainability of thin layer road markings based on their service life*
Country:	Croatia, Austria, Poland (2022)
Assessed activity:	Environmental sustainability assessment of thin-layer road markings based on their durability and required frequency of renewal
Nature of the activity:	Transport
Life cycle phases:	Operation and maintenance of road infrastructure
Goal definition:	Propose a methodology to evaluate the sustainability of road markings by combining material composition and service life performance, without resorting to full LCA
Target audience:	Scientists, policymakers, environmental managers, road authorities, and procurement officers
Scoping:	Analyzes how composition and durability of paints and glass beads influence the environmental impacts of road markings through repeated maintenance cycles; challenges current procurement practices focused on upfront cost rather than longevity
Nature of inventory data:	Field test data from Croatian road segments with varied traffic exposure; measured retroreflectivity degradation over time for multiple marking materials; material composition and use quantities were experimentally derived and calculated
Quality assessment:	Robust field measurements over up to 7.6 million vehicle passes; exponential decay modeling of retroreflectivity; statistical analysis including ANOVA and t-tests to determine significance of material choice on durability
Impact assessment:	Methodologies used for impact quantification: Life Cycle Assessment (simplified, cradle-to-grave perspective), Ozone Formation Potential (OFP) from Total Organic Gas (TOG) emissions
Environmental impact categories:	Carbon footprint, material/resource consumption (resins, TiO_2, fillers), VOC emissions, Ozone Formation Potential, microplastic pollution from abrasion
Benefit assessment methods:	Benefits quantified through reduction in resource use and emissions due to increased service life; impact per m^2 calculated across a projected 20-million vehicle pass lifespan; comparative sustainability assessed using relative consumption and emissions indicators (e.g., spider charts)

CASE STUDY NO.100

Name:	*Environmental impact assessment of CPEC: a way forward for sustainable development*
Country:	Pakistan (2021)
Assessed activity:	Environmental implications of the infrastructure and energy projects under the China–Pakistan Economic Corridor (CPEC)
Nature of the activity:	Infrastructure development and energy generation
Life cycle phases:	Planning, construction, and operation of infrastructure and energy facilities
Goal definition:	To examine the environmental consequences of CPEC-related developments and propose sustainable alternatives and legislative reforms
Target audience:	Policymakers, environmental lawyers, development planners, government agencies, and international organizations
Scoping:	The study investigates the environmental risks associated with infrastructure (e.g., roads, railways, ports), energy projects (especially coal-fired power plants), and industrial zones under CPEC, emphasizing emissions, deforestation, air pollution, and climate change vulnerability
Nature of inventory data:	Secondary data from official documents, project reports, and prior academic studies; qualitative assessment based on document analysis
Quality assessment:	Qualitative analysis using comparative legal and policy review; no empirical or statistical validation, but relies on documented environmental impacts and policy frameworks
Impact assessment:	• Methodologies used for impact quantification: • Environmental Impact Assessment (EIA) frameworks from Pakistan and China • Legal comparative analysis • Scenario-based projections (e.g., GHG emissions estimates from coal use)
Environmental impact categories:	• Greenhouse gas emissions (CO_2) • Land use change and deforestation (cutting of >54,000 trees) • Air quality (increased smog and particulate matter) • Climate vulnerability (extreme weather, glacial melting) • Biodiversity loss and ecosystem disruption • Water pollution and waste management (coal ash handling)
Benefit assessment methods:	• The study does not quantitatively assess environmental benefits but qualitatively discusses potential benefits of adopting alternatives (e.g., renewables) • Suggests legal and institutional reforms, bilateral environmental agreements, and international cooperation as pathways for benefits • Cites the potential for “pollution halo effect” and “environmental leapfrogging” if China exports cleaner technologies and environmental standards

CASE STUDY NO.101

Name:	*Selection of the variant of highway based on the territory susceptibility to landslides – model area D1/R3 highway nearby Oravský Podzámok*
Country:	Slovakia (2023)
Assessed activity:	Routing and variant selection for a new expressway section (R3) considering terrain susceptibility to landslides
Nature of the activity:	Transport
Life cycle phases:	Planning and design phase of road infrastructure
Goal definition:	To assess and compare different highway route variants based on their interaction with landslide-prone areas and select the most geotechnically suitable route
Target audience:	Urban planners, transport engineers, environmental impact assessors, policymakers, regional development authorities
Scoping:	Evaluates the potential environmental and geotechnical risks associated with proposed highway routes in a mountainous region, specifically focusing on landslide susceptibility as a critical factor during the planning phase
Nature of inventory data:	GIS-based spatial data, geological and geomorphological maps, digital elevation models, Corine Land Cover data, historical landslide records, and precipitation statistics
Quality assessment:	Verification of model performance using the Receiver Operating Characteristic (ROC) curve method, achieving 90.8% accuracy; reliance on multivariate statistical analysis using raster layers and unique conditional units (UCUs)
Impact assessment:	Methodologies used for impact quantification: Multivariate statistical analysis, ROC curve analysis, GIS-based modelling
Environmental impact categories:	• Biodiversity (indirectly through protected areas and ecosystem disturbance) • Geohazards (landslide susceptibility) • Land use (through spatial overlay of infrastructure and terrain classes)
Benefit assessment methods:	• The study does not quantify environmental benefits directly but discusses the reduction of environmental and geotechnical risk (e.g., avoiding unstable slopes, minimizing interference with built-up areas) as a qualitative benefit of variant optimization • Includes scenario comparison (four route variants + one optimized proposal) based on modelled susceptibility and landscape conflict minimization

CASE STUDY NO.102

Name:	*Assessing the environmental impact of roadway's construction on adjacent water resources: a case study of the southern part of Albania*
Country:	Albania (2022)
Assessed activity:	Impact of roadway construction on the quality of adjacent surface water bodies (Skotini stream)
Nature of the activity:	Transport
Life cycle phases:	Construction phase of road infrastructure
Goal definition:	Assessing how roadway construction activities affect the physicochemical parameters of surface water resources in the vicinity of the construction area
Target audience:	Scientists, environmental engineers, policymakers, transport planners, and environmental regulators
Scoping:	The study focuses on the environmental consequences of road construction in the southern part of Albania, particularly concerning pollution and degradation of adjacent surface water bodies. It examines parameters such as sedimentation, chemical runoff, and changes in hydrology, and discusses the implementation of best management practices to mitigate these effects
Nature of inventory data:	Field data from water samples collected at different times from the Skotini stream near the construction site. Samples were analysed in laboratories using standardised methods (ISO, APHA, SSH) for various physicochemical parameters (e.g., pH, BOD, COD, TDS, etc.)
Quality assessment:	Laboratory-based analysis of water quality using standard protocols and comparison with WHO guidelines; supported by qualitative site-specific evaluations and impact prediction based on technical project plans
Impact assessment:	Methodologies used for impact quantification: Matrix method for Environmental Impact Assessment (EIA) following Albanian legal frameworks; laboratory testing for water quality assessment based on ISO, SSH, and APHA standards
Environmental impact categories:	• Water quality (surface and groundwater) • Pollution by sediments and chemical compounds • Hydrological alterations (e.g., drainage, surface runoff dynamics) • Ecotoxicity and nutrient loading (e.g., nitrates, phosphates, ammonium)
Benefit assessment methods:	The study discusses the potential for reduced environmental impact through the implementation of Best Management Practices (BMPs), such as drainage systems, containment of chemical storage areas, and runoff mitigation techniques. These are qualitatively evaluated rather than quantitatively measured, based on effectiveness in similar contexts and regulatory recommendations

ANNEX II. ABBREVIATIONS AND ACRONYMS

AA	Appropriate Assessment
AC	Acidification
ADP_FF	Abiotic Depletion Potential - Fossil Fuels
AFS	Atomic Fluorescence Spectroscopy
AHP	Analytic Hierarchy Process
AMPA	Aminomethylphosphonic acid
ANOVA	Analysis of Variance
AoI	Area of Influence
AP	Acidification Potential
APHA	American Public Health Association
ASA	Aspect-Slope-Altitude
BACI	Before-After-Control-Impact
BC	Betweenness Centrality
BOQ	Bill of Quantity
BRI	Belt and Road Initiative
CBG	Composite Box-Girder
CCA	Canonical Correspondence Analysis
CCS	Carbon Capture and Storage
CED	Cumulative Energy Demand
CENIA	Czech Environmental Information Agency

CI	Connectivity Index
CLC	CORINE Land Cover
CLCD	Chinese Life Cycle Database
CML	Centrum voor Milieukunde Leiden
CML-IA	Centrum voor Milieukunde Leiden - Impact Assessment
COD	Chemical Oxygen Demand
DALY	Disability-Adjusted Life Years
DBH	Diameter at Breast Height
dG	Change in Global Connectivity
DCB	1,2-Dichlorobenzene equivalents
DID	Difference-in-Differences
DIANA	Finite Element Analysis Software
DNIT	Departamento Nacional de Infraestrutura de Transportes
dPC	Difference in Probability of Connectivity
EF	Enrichment Factor
EF 3.0	Environmental Footprint version 3.0
EIA	Environmental Impact Assessment
EIS	Environmental Impact Score
EIV	Environmental Impact Value
ELCD	European Reference Life Cycle Database
EMF	Electromagnetic Field
EP	Eutrophication Potential

EPD	Environmental Product Declaration
EPDs	Environmental Product Declarations
ESM	Energy System Modelling
EU	European Union
FDI	Foreign Direct Investment
FDP	Fossil Depletion Potential
FE	Finite Element
FEM	Finite Element Modelling
FEP	Freshwater Eutrophication Potential
FFBS	Free-Floating Bike-Sharing
FOSM	First-Order Second-Moment method
FSETP	Freshwater Sediment Ecotoxicity Potential
fsQCA	Fuzzy-set Qualitative Comparative Analysis
GA	Genetic Algorithm
GaBi	Ganzheitliche Bilanzierung (Holistic Life Cycle Assessment)
GDE3	Generalized Differential Evolution 3
GHG	Greenhouse Gases
GIS	Geographic Information System
GIS-MCE	Geographic Information System - Multi-criteria Evaluation
GPP	Gross Primary Productivity
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
Gtkm	Gross tonne-kilometre

GWP	Global Warming Potential
HC	Hydrocarbons
HEA	Habitat Equivalency Analysis
HF	Hydrogen Fluoride
HICs	Habitats of Community Interest
HP	Heat Pump
HSR	High-Speed Rail
HTP	Human Toxicity Potential
IAM	Integrated Assessment Model
ICE	Inventory of Carbon and Energy
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICD	Indian Construction Materials Database
ICU	Intensive Care Unit
IGN	Institut Géographique National
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
IS1 / IS2	Improvement Scenario 1 / 2
ISO	International Organization for Standardization
ITEC	Institut de Tecnologia de la Construcció de Catalunya (Institute of Construction Technology of Catalonia)
jMetal	Java-based Framework for Multi-Objective Optimization
KBA	Key Biodiversity Area

LAI	Leaf Area Index
LCA	Life Cycle Assessment
LC-MS/MS	Liquid Chromatography - Tandem Mass Spectrometry
LHK	Light Heavy Knockout
LHNB	Low-Height Noise Barrier
LICCER	Life Cycle Infrastructure Climate Calculator for Early-stage Roadmap
LNG	Liquefied Natural Gas
LST	Land Surface Temperature
LTI	Linear Transport Infrastructure
LULC	Land Use and Land Cover
LUTI	Land Use and Transport Interaction
MAETP	Marine Aquatic Ecotoxicity Potential
MAI	Metal Accumulation Index
MDP	Metal Depletion Potential
MDS	Multidimensional Scaling
MEP	Marine Eutrophication Potential
MJ	Megajoule
MODIS NPP	Moderate Resolution Imaging Spectroradiometer - Net Primary Productivity
MRSEI	Modified Remote Sensing Ecological Index
MSAM	Multi-Species Abundance Model
MTBF	Mean Time Between Failures
MTQ	Ministère des Transports du Québec (Québec Ministry of Transport)

MVC	Mammal-Vehicle Collision
NMD	Nationale Milieudatabase
NMVOC	Non-Methane Volatile Organic Compounds
NPV	Net Present Value
NTL	Nighttime Light
OD	Ozone Depletion
ODP	Ozone Depletion Potential
PCA	Principal Component Analysis
PCC	Portland Cement Concrete
PB-LCIA	Planetary Boundaries Life Cycle Impact Assessment
PCBG	Prestressed Concrete Box-Girder
PCLS	Prestressed Concrete Lightened Slab
PCSS	Prestressed Concrete Solid Slab
PEMS	Portable Emission Measurement System
PKM	Passenger-kilometres
PKT	Passenger-kilometre Travelled
PM	Particulate Matter
PM2.5	Particulate Matter 2.5 microns
PM10	Particulate Matter 10 microns
PMFP	Particulate Matter Formation Potential
PNRR	Piano Nazionale di Ripresa e Resilienza (National Recovery and Resilience Plan)
PoF	Probability of Failure

POCP	Photochemical Ozone Creation Potential
PSR	Pressure-State-Response
PSCIS	Provincial Stream Crossing Inventory System
PV	Photovoltaic
R&D	Research and Development
RAP	Reclaimed Asphalt Pavement
RC	Reinforced Concrete
RCP	Representative Concentration Pathways
RE2020	Réglementation Environnementale 2020
REC	Relative Exposure Concentration
REMIND	IAM Model
RENFE	Red Nacional de los Ferrocarriles Españoles (Spanish National Railway Network)
RFID	Radio-Frequency Identification
RFI	Rete Ferroviaria Italiana (Italian Railway Infrastructure Manager)
RI	Potential Ecological Risk Index
RMA	Reduced Major Axis
RMS	Root Mean Square
ROC	Receiver Operating Characteristic
RSW	Reinforced Soil Wall
SCB	Steel-Concrete Bridge
SDG 12	Sustainable Development Goal 12
SDGs	Sustainable Development Goals

SEA	Strategic Environmental Assessment
SESMG	Sustainable Energy System Modelling Group
SH	State Highway
SICRO	Sistema de Custos Referenciais de Obras (Reference Construction Cost Information System)
SIMBAD	French Urban Mobility Modelling Platform
SIMPER	Similarity Percentages
SMHI	Swedish Meteorological and Hydrological Institute
SSP2	Shared Socioeconomic Pathway 2
STKDE+	Spatio-Temporal Kernel Density Estimation Plus
SuDS	Sustainable Drainage Systems
TAEP	Terrestrial Ecotoxicity Potential
TEG	1,1,2,2-Tetrachloroethane Equivalent
TGD	Technical Guidance Document
TLCAM	Tsinghua-LCA Model
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRC	Tanzania Railways Corporation
TWP	Tire Wear Particles
UCUs	Unique Conditional Units
UAV	Unmanned Aerial Vehicle
URT	Urban Rail Transport
UVS	Under-Viaduct Space

VISSIM	Microsimulation Traffic Modelling Software
VOC	Volatile Organic Compounds
VOCs	Volatile Organic Compounds
WCB	Wooden-Concrete Bridge
Wet	Wetness Index
WP	Water Consumption Potential
WVC	Wildlife-Vehicle Collision
XPS	Extruded Polystyrene
ZEC	Zona Especial de Conservación (Special Area of Conservation)
ZEPA	Zona de Especial Protección para las Aves (Special Protection Area for Birds)