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RESEARCH ARTICLE

What is a Circular Road? Defining Circularity for Road Infrastructure

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Abstract

Circular economy (CE) strategies in road infrastructure (RI) remain fragmented and predominantly material-centric, with limited integration of lifecycle governance, demand reduction, and ecological regeneration. While buildings have advanced circular practices, definitions, and guidelines, the road sector lacks a sector-specific definition that reflects its long lifetimes, spatial permanence, public ownership, and continuous maintenance cycles. This study combines a literature synthesis with a stakeholder workshop to identify conceptual and practical gaps in current CE applications for RI. Findings show a dominant focus on recycled materials and construction-phase emissions, while avoidance strategies, design reimagining, long-term traceability, and end-of-life restoration remain underdeveloped. The result of this research is to propose a working definition of circular RI grounded in lifecycle planning, functional adaptability, material stewardship, ecological regeneration, and network optimisation. The definition provides a conceptual foundation for developing indicators, procurement criteria, and governance frameworks that align material cycles, infrastructure performance and ecosystem outcomes.

Keywords Circular Economy · Road Infrastructure · Lifecycle Governance

1. Introduction

There is a broad international consensus that today's linear "take-make-dispose" economy must be transformed into a circular economy (CE), where materials are kept in use and waste is minimised (Ghisellini et al., 2016). Although CE is widely promoted as a solution to climate and resource use challenges, there is still no universally accepted definition, nor clear sector-specific interpretations (Kirchherr et al., 2023). ISO defines CE as a systemic approach to keep resources circulating by recovering, retaining, or adding to their value, while the Ellen MacArthur Foundation (EMF) emphasises eliminating waste and pollution, circulating products and materials at their highest value, and regenerating natural systems (Ellen MacArthur Foundation, n.d.; ISO, 2024). However, in practice, CE is still unevenly interpreted when applied across different sectors (Singh et al., 2021). This unevenness reflects broader challenges in CE research, including conceptual ambiguity and tensions between circular aspirations and prevailing economic and institutional paradigms (Arnold, 2023).

These ambitions unfold against a backdrop of escalating global resource extraction. Since 2018, over 500 billion tonnes of raw materials have been extracted worldwide, and total extraction is projected to increase by 60% by 2060 (Circle Economy Foundation, 2024; United Nations Environment Programme, 2024). The construction sector is a priority for circular strategies given its vast material demand, emissions and generation of waste (Benachio et al., 2020; Pomponi & Moncaster, 2017). While CE strategies for buildings have progressed, such as with modular design, and reuse of components, adoption in road infrastructure (RI) remains limited with little system-wide implementation (Kamali & Hewage, 2016; Lamb et al., 2022; Mantalavos et

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al., 2019; Mantalovas et al., 2020; Ossio et al., 2023). The global road network currently exceeds 16 million kilometres and is projected to expand by an additional 25 million kilometres by 2050 (Barbieri et al., 2021). Roads represent the second largest stock of in-use materials after buildings, accounting for 14-32% of global totals (Grossegger et al., 2024). In mature road networks, over half of new material inputs are consumed by maintenance, underlining the sector's ongoing resource intensity (Grossegger et al., 2024).

Unlike buildings, whose footprints are discrete and localised, roads form extensive corridors that fragment landscapes and habitats, modify hydrology, and alter ecosystems, which makes their transition to circular frameworks particularly urgent (Coffin, 2007; Ibisch et al., 2016). Nevertheless, research on CE in RI has largely focused on material substitution, recycling, and construction-phase carbon reductions, particularly in asphalt technologies (Mantalovas et al., 2020). While these approaches can deliver incremental efficiency gains, they often leave broader systemic issues underdeveloped (Kirchherr et al., 2023). These include demand reduction and avoidance of new construction, land use change and ecological impacts, operational pollution, long-term traceability, and planning for end-of-life (EoL) phases. Decommissioning and ecological restoration, despite their potential for both resource recovery and ecosystem regeneration, are rarely integrated into project planning or execution (Mantalovas et al., 2020; Vetnes et al., 2026).

The lack of a coherent CE definition for RI limits policy coherence, increases the potential for greenwashing, and skews practice to focus myopically on recycled materials or short-term carbon accounting, rather than systemic, lifecycle strategies (de Waal, 2021; Hill et al., 2025; Kirchherr et al., 2023; Zuluaga et al., 2025). This is particularly consequential in the road sector, where infrastructure is predominantly planned, financed, owned, and maintained by public authorities (Rijkswaterstaat et al., 2022), positioning circularity as a challenge of long-term stewardship rather than discrete project optimisation (Kirchherr et al., 2023).

This paper proposes a working definition of circular RI grounded in a lifecycle and systems perspective. Drawing on a semi-structured review of sustainable RI literature and a multi-stakeholder workshop, the paper reframes circularity to reflect the temporal, ecological, and governance characteristics of RI. The establishment of a working definition which follows basic guiding CE principles is intended to be a springboard to better design and resource use in RI. The proposed definition aims to support future research, CE indicator development, circular procurement practices, and policy instruments tailored to RI which go beyond a narrow focus on materials and CO2 emissions.

2. Methods

This study employed a mixed-methods approach combining a synthesis of applicable CE literature with a stakeholder workshop. This design enabled the integration of conceptual and practice-based perspectives. A semi-structured scoping review provided a broad theoretical foundation and insights from international studies, while the workshop captured context-specific priorities, feasibility assessments, and practical challenges.

2.1. Literature Collection and Scope

A semi-structured literature search was conducted using the Scopus database to identify peer-reviewed academic publications addressing CE principles in the context of RI. The CE principles in this context relate to the basic EMF framework for CE, where three main principles are defined in Figure 1. The EMF framework was chosen due to it being widely accepted among practitioners and it is neither too broad nor too restrictive.

The basic framing of RI lifecycle is also necessary to establish a basic scope for the literature review. In this study, the lifecycle phases follow the ISO59004 general definition (ISO, 2024) and are defined within this study as: i) *Planning and Design*, ii) *Construction*, iii) *Operation and Maintenance*, iv*) End-of-life (EoL) and Decommissioning*, and v) *Governance and Procurement*. Governance and Procurement is explicitly distinct from the technical-focused Planning and Design, as the focus here is on how wider implementation of CE in RI can be accomplished.

Figure 1. Principles of CE as defined by the Ellen Macarthur Foundation (Ellen MacArthur Foundation, n.d)

The Scopus database was used for the literature search and was limited to English-language, peer-reviewed articles. A broad search string was chosen to gather a list of preliminary sources before further screening. The following search string was applied:

"Circular economy" OR "circular design" AND road OR highway AND construction OR Infrastructure

This search returned 405 articles. Screening followed a staged approach. First, titles were screened for relevance to RI as a physical and operational system, resulting in 70 articles retained for abstract screening. Articles were excluded at this stage if the terms "road" or "highway" were used metaphorically (e.g. "road to …", "roadmap"), or if the study did not scope RI as an asset, network, or lifecycle system.

Abstracts were screened to assess whether the paper addressed circularity beyond the use of recycled or secondary materials in pavement construction. A substantial share of the literature focused narrowly on material substitution or waste valorisation within otherwise conventional road design and delivery models. While such studies contribute important insights on material efficiency, they typically did not engage with broader questions of CE and/or lifecycle phases beyond the material production phase. Articles limited to these material-centric framings were therefore excluded from full-text review due to their limited scope (i.e. only a single lifecycle phase) as they did not incorporate CE holistically. Following abstract screening, 25 articles were retained. While excluded from full-text analysis, material-focused studies were documented to contextualise dominant research trend within the field. Following full-text screening, snowballing was conducted to capture potentially relevant literature not identified through the database search. This included backward snowballing through reference lists of the identified articles, and forward snowballing via citation tracking of the key publications. In addition, selected grey literature was included to capture policy frameworks, regulatory instruments, and practice-oriented guidance shaping CE implementation in RI. This literature was identified through targeted searches, and was treated as contextual and institutional inputs rather than as primary evidence.

The literature synthesis was qualitative and conceptual in nature, aiming to synthesise dominant framings of CE in RI and identify systemic gaps, rather than to assess or compare quantitative performance outcomes. Accordingly, the review does not constitute a systematic review or meta-analysis, but a semi-structured scoping and synthesis exercise to support theory development and definition-building.

2.2. Stakeholder Workshop

A stakeholder workshop was held on 17 March 2025 in Oslo, Norway to gather practice-based insights and evaluate the applicability of CE concepts in RI. The programme combined short talks with facilitated breakouts on defining circularity for RI and how to measure circularity in practice, followed by plenary summaries and a short individual questionnaire. This article only uses the workshop activities that focused on defining circularity for RI.

A total of 26 participants attended the workshop, representing key actors in the Norwegian road infrastructure value chain, including planners, consultants, contractors, researchers, and public road authorities. Thirteen participants completed the post-workshop questionnaire. The range of professional roles ensured that perspectives from planning, design, delivery, operation, and governance were represented.

To guide discussion, participants were asked: "*What essential elements should be included when evaluating the circularity of road projects*?" Workshop output, based on written group notes and post-workshop questionnaire responses, were digitalized and coded according to the same lifecycle definitions and CE principles as used in the literature review. Similar statements were grouped together to highlight dominant understandings of circularity, perceived gaps, and implementation barriers. These findings were then compared with insights from the literature review to assess areas of alignment and divergence between research and practice. These Interactive sessions facilitated knowledge exchange between participants, thereby complementing the conceptual literature with context-specific expertise.

3. Results & discussion

3.1. Current Status for CE in RI

The semi-structured review revealed that a substantial share of CE-related research on RI focuses primarily on material substitution, recycled content, and construction-phase carbon reduction (e.g. asphalt technologies). While these approaches contribute to improved resource efficiency, they tend to frame circularity at the level of discrete projects and material inputs. However, RI is more than the sum of its physical components. Their construction and operation reshape adjacent environments through land take, barrier effects, and altered surface and sub-surface hydrology, which can even reduce natural carbon sequestration potential in nearby landscapes (Coffin, 2007; Saraswati et al., 2023). Yet RI planning typically assumes permanence and seldom incorporates future decommissioning that could help alleviate environmental harms (Barandica et al., 2013; Mantalavos et al., 2019). A circular approach should therefore account for continual lifecycle maintenance and material demand, operational externalities, planning for EoL and decommissioning, and implementing measures to reduce the need for new RI.

Mature road networks exhibit "material saturation", where more than half of new material inputs are devoted to operation and maintenance rather than new construction (Grossegger et al., 2024; Miatto et al., 2017). In such contexts, resource consumption is driven less by expansion and more by the continual renewal of RI assets (e.g. resurfacing, drainage, markings, and structural components). These recurring interventions replicate many of the burdens associated with initial construction. Consequently, implementing circularity in RI cannot be reduced to improving resource efficiency or increasing recycled content at the project start. Instead, circular strategies must address these recurrent material flows and do so at system scale.

Operational externalities remain under-recognised within CE discussion for RI. Non-exhaust emissions from tyre, brake, and road wear now constitute a significant share of particulate burdens and microplastic releases (Leonard & Hochuli, 2017). Interpreting the first EMF CE principle of eliminating waste and pollution in the context of RI requires design and maintenance regimes that minimises or prevents pollution during use, not only waste generated across the lifecycle. Practical implications include the use of vegetated/engineered verges and drainage systems to intercept particulates, microplastics, and metals, alongside maintenance practices that minimise runoff throughout the use phase (Bai et al., 2010; Sillars-Powell et al., 2020).

Planning practices for RI generally lack functional endpoints, as areas where roads have been built are seldom planned to be repurposed or returned to nature, even though demographic and economic shifts can render segments redundant over time. Without explicit strategies for obsolescence and planned reversibility, opportunities for material recovery and ecological restoration are missed (Leendertse et al., 2018; Vetnes et al., 2026). Decommissioning of RI therefore represents a potentially regenerative strategy, enabling selective dismantling, material recovery, and reconnection of habitats where road functions are no longer required (Lloyd et al., 2013; Switalski et al., 2004; Vetnes et al., 2026).

In the absence of a systemic approach linking planning, design, construction, maintenance, and eventual removal, major opportunities for resource recovery and sustainability are lost. Equally underdeveloped are "avoidance strategies", such as measures that reduce the overall demand for new road construction by addressing transport needs by other means (Mantalavos et al., 2019). From a CE perspective, such strategies align with the upper tiers of widely used circular hierarchies, often framed as refuse and rethink, where resource use is avoided instead of just improving downstream efficiency measures (Leendertse et al., 2018; Ossio et al., 2023). Demand management policies that limit unnecessary car travel (i.e. through congestion charges, tolling incentives for shared mobility) or modal shift strategies that encourage movement from private vehicles to public transportation, cycling, or walking, can lower the pressure to expand existing road networks (Hasan et al., 2019; Jalas & Numminen, 2022; Meyer, 1999). Similarly, network optimisation strategies focusing on making better use of existing RI, for instance by improving traffic management, upgrading bottlenecks, or repurposing underused segments, should be prioritised rather than building new capacity (Zuluaga et al., 2025).

Avoidance strategies conflict with prevailing growth-oriented infrastructure planning paradigms, where expansion is often treated as the default response to mobility demand (Busscher et al., 2015). This tension reflects broader evidence that the adoption and integration of CE strategies vary significantly across institutional and socioeconomic contexts, influencing how circularity is prioritised within infrastructure systems (Durán-Romero et al., 2025).

As a result, avoidance is rarely conceptualised as a form of circularity in RI, despite its capacity to eliminate material extraction, land take, and ecological disturbance at the outset. From a systemic CE perspective, this conflict highlights a fundamental challenge: circularity in RI cannot be fully realised through material loops alone if demand-side decisions and network-scale planning logics remain outside of the scope of CE frameworks (Zuluaga et al., 2025).

3.2. Workshop Findings and Conceptual Gaps

Figure 2. Word cloud of workshop responses to "What essential elements should be included when evaluating the circularity of road projects?"

The workshop offered an entry point into how practitioners currently frame CE in RI. Participants were asked to discuss in groups the question "*What essential elements should be included when evaluating the circularity of road projects*?" Responses were dominated by terms such as "recycling", "reuse", and "resource efficiency" (a response word cloud can be seen in Figure 2), which indicates awareness of material-oriented practices but also a narrow interpretation of CE. Participants tended to equate circularity with higher recycled content and reduced embodied carbon at construction stage.

Participants' perceptions remain focused on material inflows rather than whole-lifecycle strategies that align with the principles of EMF and ISO's system-level definition. Systemic and temporal dimensions, such as demand reduction, design for disassembly (DfD), long-term traceability and stewardship of materials, prevention of operational pollution, and reversibility at EoL were not considered by participants.

The combined effect is an implementation gap where CE terminology is increasingly adopted in RI discourse, but practices remain partial and construction-centric, with emphasis on emissions reduction and material recycling (Leendertse et al., 2018; Mantalavos et al., 2019; Mantalovas et al., 2020). Framing circularity only as a resource issue also neglects the road's societal role. As social and territorial systems, roads shape mobility patterns, land use, and equity over long time horizons. This reinforces the importance of planning-stage decisions, as central elements of Circular RI, rather than as external considerations beyond the scope of CE.

3.3. Toward a Framework for Circular Roads

A road is not a monolithic structure with a single lifespan but a composite system with differentiated technical and economic cycles. Pavement layers, bridges, drainage systems, safety installations, and surrounding land each operate on different temporal scales and replacement intervals. For example, asphalt surfaces may require renewal within a decade, while bridges can remain for half a century or more (Leendertse et al., 2018). Circular strategies must therefore accommodate differentiated lifespans and avoid treating RI as a uniform material stock.

Lifecycle Phase	EMF Principle 1: Eliminate Waste & Pollution	EMF Principle 2: Circulate Products & Materials at Highest Value	EMF Principle 3: Regenerate Nature
Planning & Design	Expansion led planning persists; demand management secondary despite strong induced-demand evidence	Future material flows seldom drive design; DfD concepts are rare in roads/bridges	Ecological impacts often minimised/mitigated rather than avoided
Construction	Compliance focused on emissions standards; waste minimisation secondary to cost and speed	High use of RAP in asphalt, recycled aggregates in bases, but mostly for downcycling; continuous circulation underdeveloped	Nature loss usually permanent; offsetting limited or absent
Operation & Maintenance	Pollution (runoff, noise, traffic emission) managed but not eliminated	Virgin demand remains high; reuse and recovery options underdeveloped	Ecological disruption persists throughout lifecycle
EoL/ Decommissioning	Rarely planned for, deconstruction guidelines largely absent	Material recovery is ad hoc and poorly planned; high-value materials are frequently downcycled or lost due to lack of design for reuse	Opportunities for renaturing seldom taken; biodiversity and carbon benefits often missed
Governance & Procurement	Lowest upfront cost prioritised; weak incentives to avoid waste	Material traceability is emerging, not standard	Policies optimise rather than restore; regenerative outcomes remain outside mainstream practice

Figure 3. Critical gaps and opportunities in current practice for circular RI

To synthesise the gaps identified in the literature (Section 3.1) and the practitioner framings observed in the workshop (Section 3.2), Figure 3 maps lifecycle phases of RI against the three core principles from EMF. The rows represent the lifecycle phases of RI while the columns correspond to core CE principles. The colour coding illustrates the degree of alignment between current practice and these principles. Red cells indicate significant gaps or weak integration, yellow cells reflect partial or emerging alignment, and green cells denote comparatively stronger implementation. Eliminating Waste and Pollution (EMF Principle 1) is most predominant during the construction and operation and maintenance (O&M) phase, but is typically regarded as a waste problem instead of an opportunity for circularity with better planning and design. Circulating Products and Materials at Highest Value (EMF Principle 2) is most well developed in the construction phase, especially with the use of RAP in asphalts. Opportunities for use of circular and secondary waste materials remains underutilized while planning for re-use of RI and materials is not found to be common in road construction practice, and when utilized, it is done so on an ad-hoc basis as opposed to a construction standard. Regeneration of Nature (EMF Principle 3) is not well covered in RI construction practices. There is general acceptance for RI to disrupt nature, and few examples where disruption to nature is regarded as important and avoidable. There are also few examples of prioritizing nature regeneration in road construction projects. The predominance of red and yellow cells across phases highlights systemic misalignments rather than isolated shortcomings. Figure 3 therefore illustrates that incremental improvements within individual lifecycle stages are insufficient to achieve systemic circularity. Alignment with CE principles requires coordinated effort, rather than a narrow focus on material substitution or construction-phase performance.

Several patterns emerge in these results: First, circular considerations are weakest at the earliest and latest stages of the RI lifecycle. Planning and design remain expansion-oriented, with limited integration of demand reduction or DfD, while EoL and decommissioning strategies are rarely embedded in project design (Busscher et al., 2015; Vetnes et al., 2026). Second, material looping efforts are concentrated in construction, particularly through RAP and aggregate substitution, but often take the form of downcycling rather than high-value reuse. Third, regenerative outcomes are marginalised across all phases, with ecological impacts typically mitigated rather than avoided or reversed (Hennig et al., 2026). The governance and procurement dimension show that incentive structures frequently prioritise lowest upfront cost, while long-term material traceability, reversibility, and regenerative objectives remain weakly institutionalised (Hennig et al., 2026; Vetnes et al.,

2026). This indicates that circularity in RI is not solely a technical design issue, but also a question of lifecycle stewardship embedded in public-sector planning, procurement, and asset management frameworks.

3.3.1. Long-term Planning for Road Materials and Nature Across Full Asset Lifecycle Aligning RI with CE principles requires that planning extend across the full asset lifecycle rather than concentrate primarily on the construction-phase. In the planning and design phase, infrastructure capacity must be matched to projected demand, and assets should be designed for adaptability to avoid overbuilding or premature obsolescence. This directly addresses the expansion-oriented design identified earlier and situates circularity at the level of network strategy rather than within isolated projects.

During construction, ground disturbance should be minimised and composite assemblies which mix materials should be avoided so that materials remain recoverable at later stages (Hendriks et al., 2020). Research demonstrates that construction practices that limit irreversible soil transformation and material entanglement substantially improve future recovery potential and reduce environmental burdens (Hennig et al., 2026). Planning for recycling of materials must be paired with strategies for reuse, traceability, and DfD (Eberhardt et al., 2022; Leendertse et al., 2018). In operation, non-exhaust emissions and runoff should be addressed at the source (Leonard & Hochuli, 2017). At EoL, assets should be designed to be dismantled selectively, and planning for restoration of land and regeneration of ecosystems should be implemented where RI function becomes obsolete. Since roads occupy land and fragment habitats, planning for ecological regeneration is crucial to restore ecological functions such as habitat connectivity, hydrological processes, and carbon stocks, both during operation and at decommissioning (Coffin, 2007; Ibisch et al., 2016). Research on biodiversity restoration in road projects emphasises that ecological outcomes must be addressed through the mitigation hierarchy, prioritising avoidance and minimisation before restoration or offsetting, and highlights the need to account for both the extent and quality of restored habitats (Hennig et al., 2026). Taken together, lifecycle planning reframes circularity in RI as a long-term stewardship challenge integrating material, ecological, and functional dimensions.

3.3.2. Design Choices for CE in RI While lifecycle planning establishes a temporal scope of circularity, implementation depends on concrete design strategies at the component and system level (Ghisellini et al., 2016; Ossio et al., 2023). A circular framework must recognise the road as a composite system whose elements age and are replaced at different intervals.

Early design decisions are therefore decisive. Circular design strategies such as modularity, standardised interfaces and DfD enable separation, upgrading, and high-value reuse of pavements, barriers, deck elements, and sub-structure components (Wu et al., 2025). However, despite its recognised potential to support circular material flows, DfD remains limited in mainstream construction practice, underscoring the need to operationalize such principles more systematically in infrastructure systems (Heisel et al., 2025). These approaches reduce mixed material streams, inseparable connections, and non-standardised components that otherwise lock infrastructure into linear replacement cycles that impede resource recovery (AlJaber et al., 2025). Circular design must also be aligned with carbon and energy objectives (Fragkos, 2022). Integrating DfD with low-carbon materials and energy-efficient operational strategies allows design decisions to deliver simultaneous gains across circularity, carbon reduction, and energy performance rather than treating these as separate agendas.

3.3.3. Traceability/Stewardship as a Challenge High-value circulation of materials depends not only on physical separability but also on long-term traceability (Davari et al., 2023). Digital product passports (DPP) under the EU Ecodesign regulation aim to keep persistent materials data and compliance attributes available throughout an asset's lifecycle (Office Journal of the European Union, 2024). Sector-specific proposals for RI further illustrate how traceability can be operationalised for long-lived assets, while also highlighting the complexity of collecting and maintaining reliable lifecycle data (Senarathne et al., 2025).

In RI traceability is primarily an institutional challenge. Infrastructure lifetimes span decades and often multiple contractors, owners, and governance reforms. Effective traceability therefore requires interoperable identifiers, clearly defined stewardship responsibilities, contractual obligations to update records at each intervention, secure long-term data hosting arrangements, and procurement frameworks that render

information auditable and transferable between actors (Lamb et al., 2022; Leendertse et al., 2018). Empirical work on circular renovation projects further demonstrates that establishing dedicated data roles, shared asset platforms, and clearly sequenced information exchanges across project phases is essential for enabling reuse and informed decision-making in practice (Entrop et al., 2022). Without such governance mechanisms, traceability risks remaining fragmented and insufficient to support systematic reuse or regeneration.

3.3.4. Standardisation and Scaling Standardisation is rarely addressed in current circular RI literature, yet it may prove decisive for scaling circular practices. Modular and reusable components can only circulate at scale if design specifications and contracting practices enable interoperability across projects and jurisdictions (Leendertse et al., 2018; Rijkswaterstaat et al., 2022; Wu et al., 2025).

Standardisation reduces transaction costs, increases predictability, and enable systematic reuse rather than isolated experimentation. Alignment with the EU Ecodesign for Sustainable Products Regulation (ESPR), including requirements for durability, repairability, recycled content and Digital Product Passports, can embed circular criteria within mainstream procurement systems (Office Journal of the European Union, 2024; Wu et al., 2025). Circularity, carbon, and energy performance should therefore be managed as an integrated strategy. Standardised frameworks ensure that design requirements advance multiple objectives simultaneously rather than optimising one at the expense of the others.

3.3.5. Synthesis of Framework Elements

Figure 4. Circular economy dimensions for road infrastructure

The proposed framework for circular RI rests on five interdependent dimensions (Figure 4), that together reposition circularity in RI from a construction-phase material optimisation exercise to a coordinated lifecycle, ecological, and governance framework capable of addressing material flows, land use, and long-term network performance:

1. *Lifecycle planning*: Adoption of a temporal perspective that recognises differentiated component lifespans and the possibility of functional obsolescence at system level.
2. *Circular design strategies*: Modularity, DfD, and differentiated lifespans that enable high-value reuse, upgrading, and selective recovery.
3. *Ecological integration*: Treatment of land occupation, habitat fragmentation, carbon stock preservation, and ecosystem regeneration as central criteria of circularity rather than external project constraints.
4. *Traceability and stewardship*: Institutional mechanisms that ensure long-term material transparency, accountability, and continuity of information across decades of asset management.
5. *Standardisation for scale*: harmonised design and procurement frameworks that enable interoperability and systematic material circulation across projects.

3.4. Defining Circularity of Road Infrastructure

Sections 3.1-3.3 demonstrated that current CE applications in RI remain fragmented and predominantly material-centric, with limited integration of demand reduction, lifecycle governance, and ecological regeneration. While incremental improvements in recycling and emission reduction are evident, alignment with the full scope of CE principles remains partial. At the same time, the preceding framework illustrates that a more comprehensive reorientation is conceptually and institutionally feasible.

Lifecycle Phase	EMF Principle 1: Eliminate Waste & Pollution	EMF Principle 2: Circulate Products & Materials at Highest Value	EMF Principle 3: Regenerate Nature
Planning & Design	Prioritises demand reduction, modal shift, and network optimisation before new construction	DfD, modularity, and material passports are incorporated using open data standards; design allow mid-life adaptability	Integrates habitat connectivity, protects existing carbon stocks, and plans biodiversity corridors
Construction	Uses low-carbon materials, minimal site disturbance, and enforces embodied emissions limits	Maximised use of secondary/renewable materials; quality and traceability enable closed-loop, high-value recycling and remanufacture	Adapts construction to preserve soils hydrology, minimise ecosystem damage, and regenerates adjacent terrain as possible
Operation & Maintenance	Pollution prevention is integral	Maintenance strategies prioritise modular reuse, refurbishment, and design-in adaptability to extend life and	Routine upkeep includes green infrastructure (pollinator zones, vegetated buffers), and maintenance practices adjusted to ecological goals.
EoL/ Decommissioning	Deconstruction is planned early; infrastructure components are designed for reversibility and least disruption	High-value recovery through selective dismantling, reuse, remanufacturing, supported by standards	Ecological restoration and renaturing are embedded in project closure
Governance & Procurement	Procurement based on life-cycle cost, carbon budgets, and CE performance metrics	Digital tools, material traceability, open data, and interoperable systems ensure transparency and circular metrics	Policies mandate regenerative outcomes and social value (equity, safety, access), aligning network optimisation with ecosystem recovery and carbon sequestration

Figure 5. Alignment of RI lifecycle phases with CE principles as a framework for an idealised circular road

Figure 5 uses the same lifecycle phases and CE principles as Figure 3 to map a future state of practice, where each cell reflects full rather than partial alignment with CE principles, the potential for a comprehensive reorientation is clear. A sector specific framework for circular RI must therefore extend beyond CE practice (or lack of) to encompass resource demand reduction, resource traceability, functional adaptability, and ecological regeneration (Busscher et al., 2015; Circle Economy, 2025; Eberhardt et al., 2022; Hennig et al., 2026; Meyer, 1999; Ossio et al., 2023; Rijkswaterstaat et al., 2022; Vetnes et al., 2026; Wu et al., 2025). Figure 5 does not represent a predictive or empirical assessment of achievable outcomes. Rather, it functions as a normative reference point that articulates what full alignment between RI lifecycle phases and CE principles would require if institutional, technical, and ecological dimensions were addressed together. This approach draws on the logic of transition management, in which long-term sustainability visions serve to orient short-term experiments and governance decisions without prescribing a fixed endpoint (Loorbach, 2010). The value of the framework shown in Figure 5 lie not in its immediate attainability, but in its capacity to expose the distance between current fragmented practice and genuinely systemic circularity for RI, and to provide a directional reference for the future development of indicators, procurement criteria, and governance frameworks beyond this paper.

Taken together, the framework outlines a conceptual path towards circular RI that is useful for developing a working definition for circular RI. Based on this analysis, we propose the following definition:

A circular road is planned, designed, constructed, operated, maintained, and, where appropriate, decommissioned using a systemic, lifecycle approach that keeps virgin resource inflows as low as possible and maintains circular flows of resources by recovering, retaining, and adding value to materials and components. It minimises waste, material losses, and pollution; keeps products and materials in use at their highest value through maintenance, reuse, refurbishment, remanufacture, and high-quality recycling enabled by traceability; and is designed for adaptability and potential disassembly. It preserves and regenerates ecosystems and contributes to sustainable development, delivering long-term societal value by aligning material cycles, functional performance, and road-network optimisation.

This definition differs from general CE formulations in three key respects. First, it explicitly integrates demand reduction and network optimisation, positioning avoidance of new construction as a central circular strategy rather than a peripheral transport policy measure. Second, it embeds ecological regeneration and land stewardship as intrinsic components of circularity in spatial infrastructure systems, rather than treating environmental mitigation as external add-ons. Third, it frames circularity as a matter of long-term governance and stewardship, recognising the public sector responsibility for maintaining information continuity, reversibility, and lifecycle accountability across decades. By aligning material cycles, functional performance, ecological outcomes, and institutional mechanism, the definition moves beyond construction-phase optimisation and provides a foundation for developing indicators, procurement criteria, and regulatory instruments tailored to RI.

3.5. Institutional Dynamics for Implementing CE in RI

An important finding is the divergence between RI and buildings in adopting CE principles. Buildings, largely privately developed, have advanced through market incentives, certification schemes, and innovative design (Ossio et al., 2023). Roads, by contrast, are predominantly planned, financed, owned, and maintained by public authorities (Rijkswaterstaat et al., 2022). In principle, this centralised role could facilitate early and coordinated adoption of circular principles, as all lifecycle phases fall within interconnected public mandates. In practice, however, the transition has been slow with several challenges still to overcome. Fragmented responsibilities across agencies and project phases, limited institutional risk tolerance in publicly founded infrastructure, and investment paradigms that prioritise network expansion and short-term capital cost over lifecycle value have constrained systemic change (Arts et al., 2021; Busscher et al., 2015; Rijkswaterstaat et al., 2022). These structural conditions help explain why circularity in RI often remains confined to incremental material efficiency measures rather than lifecycle reorientation.

Public procurement emerges as the most powerful yet underutilised lever for implementation. By embedding lifecycle costing, performance-based contracts, and explicit circular criteria in tender processes, public buyers can shift incentives from lowest upfront cost toward long-term value retention (Liu & Kringos, 2024; Perera & Morton, 2009; Sönnichsen & Clement, 2020). Circular public procurement has been identified as a key mechanism for embedding lifecycle criteria into project delivery, yet existing practices often remain constrained by cost-driven evaluation models (Vanacore et al. 2023).

Effective mechanisms include tender evaluation based on lifecycle cost and project-level carbon budgets; specifications requiring DfD, standardised interfaces, and verifiable material passports; and performance-based maintenance contracts that assign material stewardship and EoL recovery obligations to contractors (Schraven et al., 2023). Complementary business models, such as material leasing or "infrastructure as a service", further reinforce a shift from construction-centric delivery toward lifecycle governance. These models redistribute risk and responsibility across longer time horizons, aligning contractor incentives with durability, adaptability, and recoverability. The persistence of linear practices in RI thus appears to stem less from technical infeasibility than from institutional inertia, contractual fragmentation, and misaligned incentives (de Jesus & Mendonça, 2018; Schraven et al., 2023).

Path dependency compounds challenges towards circular RI, as once roads are constructed, settlement patterns and economic activity adapt around them, making decommissioning or functional repurposing politically and socially complex, even when technically feasible (Baum-Snow et al., 2020; Marein, 2022). In rapidly expanding economies, where networks are still being built rather than maintained, the obstacles and opportunities for circularity may differ; the transferability of ideas should therefore be encouraged (Zuluaga et al., 2025).

Ultimately, the institutional configuration of the road sector positions the public sector in a unique triple role as regulator, commissioner, and long-term asset owner. If circularity in RI is understood as a problem of lifecycle governance and stewardship instead of a narrow material efficiency and CO_2-emissions reduction exercise, public authorities are uniquely placed to align mandates, procurement systems, and regulatory frameworks accordingly. The implementation of the proposed definition therefore depends not only on technical innovation, but on institutional coordination capable of integrating material, ecological, and functional objectives across the full infrastructure lifecycle. In particular, planning and procurement mandates must recognise demand reduction and network optimisation as legitimate circular strategies, rather than treating expansion as the default response to mobility demand. Without institutional space for avoidance-oriented decisions, circularity risks remaining confined to incremental material improvements within fundamentally linear growth trajectories.

4. Conclusion

This paper has argued that CE approaches in RI remain fragmented and predominantly material-centric, with limited integration of demand reduction, lifecycle governance, and ecological regeneration. While recycling and emissions reduction initiatives represent important progress, they do not constitute systemic circularity in a sector characterised by long lifetimes, spatial permanence and public-sector stewardship. We therefore proposed a sector-specific definition of circular RI grounded in five interdependent dimensions: *lifecycle planning, circular design strategies, ecological integration, traceability and stewardship, and standardisation*

for scale. This reframing positions circularity not as construction-phase optimisation, but as coordinated governance throughout the planning, design, operation, and decommissioning phases. A genuinely circular road system integrates demand management and network optimisation to avoid unnecessary expansion, enables adaptable and disassemblable components with differentiated service lives, reduces operational pollution, and embeds ecological regeneration. Implementation depends on material traceability, interoperable standards, and procurement and regulatory frameworks that align circularity, carbon, and energy objectives over time.

Future research should focus on developing circularity indicators that move beyond recycled content metrics and capture lifecycle, ecological, and demand-side dimensions. Further work is needed to test governance models that institutionalise long-term stewardship across multiple project cycles, and to empirically evaluate decommissioning and ecological restoration strategies in mature road networks. Finally, research on digital traceability should examine long-term data governance, interoperability, and the risks of technological obsolescence over infrastructure lifetimes.

Ultimately, improving the circularity of individual road components does not render the system circular. Only a holistic, lifecycle-oriented approach that aligns material cycles, functional performance, institutional incentives, and ecosystem outcomes can meaningfully reposition RI within a circular economy.

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Data availability Data will be made available upon written request to the author(s).

Declarations

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