

REVIEW

Green and Near-Zero Carbon Highways: A Review of Next-Generation Low-Carbon Construction Technologies and Near-Zero Carbon Operation

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ABSTRACT

Highways are a vital component of global transportation infrastructure, but their environmental impact, particularly in terms of carbon emissions, poses significant challenges to achieving global sustainability and climate goals. This literature review discusses the new area of low-carbon highways, including next-generation construction technologies and near-zero carbon operation strategies. It discusses the purpose of innovative materials, such as low-carbon cements, recycled asphalt, and geopolymers, and intelligent infrastructure solutions, including intelligent traffic control and electric vehicle charging systems. The article also explores the significance of Lifecycle Assessment (LCA) and carbon accounting in the measurement and minimization of the carbon footprint of highways. Even though a lot of progress has been made, there are still several technical, economic, and regulatory obstacles, among which are the prohibitive initial cost of low-carbon technologies and the non-standardization of policies. The future outlook indicates that to alleviate these challenges, a coordinated effort among the research, policy, industry, and communities is necessary. Low-carbon highways can help to have a robust, sustainable transport system that meets global climate goals by incorporating sustainable processes in highway design, construction, and operation.

Keywords: Low-Carbon Highways; Lifecycle Assessment (LCA); Carbon Accounting; Smart Infrastructure; Sustainable Materials

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1. Introduction

Highway construction and operation are a major part of infrastructure development, with the construction of highways worldwide directly influencing transport, economic development, and social connectivity. Nevertheless, highways and the transportation industry overall contribute significantly to the overall greenhouse gas (GHG) emissions in the world, both in the form of embedded carbon in the construction materials and in operations based on vehicle traffic. As the need to tackle the climate change menace and fulfill international climate obligations increases, there has been a sharp transition to the idea of sustainability in the various infrastructure sectors, and the transportation industry is no exception. To this, the idea of green highways has been proposed, which is concerned with the low-carbon material, technology, and sustainable operational practices with the aim of minimizing the carbon footprint of highway infrastructure across the entire life cycle^[1,2].

When it comes to highways, one will consider a major environmental impact based on the fact that construction materials that are being used are based on carbon, i.e., concrete and asphalt. It is believed that the World Road infrastructure industry contributes to almost 40 percent of all global carbon emissions in the construction and operation of infrastructure, as cited by the World Road Association (PIARC). This is exacerbated by the fact that the building of highways involves the use of cement, steel, and the traditional type of asphalt, which are energy-intensive and will emit a lot of CO₂. Moreover, the environmental footprint of highways is enriched by operational emissions produced by vehicles passing through these roads while consuming fuel and causing traffic congestion. This is a twofold problem of embodied and operational carbon that is essential to be resolved in the shift to sustainable transport infrastructure^[3-5].

The trend towards the development of near-zero carbon highways is spreading as the solution to the challenges of infrastructure that should be consistent with the global practices of carbon neutrality, including the provisions of the Paris Agreement. Nations around the globe have stipulated high targets that can be reached by the middle of the century to have a net-zero emission, and transportation infrastructure is leading this battle. National policies and road sector strategies are being formulated in most regions to minimize emis-

sions of carbon in road construction and operation. Besides, some international programs, such as the UN Sustainable Development Goals (SDGs), request the infrastructure development that reduces environmental degradation, integrates energy efficiency, and enables climate resilience^[6].

The green highways initiative includes innovations in the total lifecycle of highway infrastructure, including materials, design, construction, operation, and maintenance. Although much concern has centered on the minimization of carbon emissions during the construction stage through the exploitation of low-carbon materials and the use of energy-efficient construction methods, it is also important to focus on the operational stage of highways. Traffic management systems, sustainable maintenance, and energy-efficient technology can significantly lower the carbon emissions caused by the work of highways, which will also lead to the further aim of near-zero carbon highways^[7].

This review will seek to present an effective synthesis of third-generation low-carbon construction technology and near-zero carbon operations strategies of highways. The aim is to examine the research in materials science, engineering, and operational strategies that can make a significant contribution to the reduction of carbon emissions in the construction, maintenance, and use of highways. Through the analysis of various innovative materials, including low-carbon cements, recycled materials, and energy-efficient construction techniques, we will find out the most important technologies, which promise to turn the highway infrastructure industry into a more sustainable and low-carbon industry^[8].

Also, the review will concentrate on the near-zero carbon operation, which implies the role of digital technologies, intelligent traffic systems, and sustainable maintenance practices in mitigating the emissions of highways in operation. These intelligent systems of traffic management, energy harvesting technologies built into the road surface, as well as advanced monitoring instruments for predictive maintenance, are components of a wider plan of reducing emissions throughout the entire lifecycle of a highway. Moreover, since highways are the major links in the transport networks both nationally and internationally, converting them to near-zero carbon infrastructure also provides a possibility to stimulate the changes in the wider society towards sustainability in the transportation domain^[9].

Though the steps in the right direction are being

achieved, the overall implementation of these low-carbon systems has been hampered by a number of challenges, such as high initial cost, technology availability, administrative challenges, and the requirement for more research and development. More so, there are still major challenges as far as standardizing the techniques of measuring the carbon footprint of highways is concerned, especially when they are running as well as in their lifecycle.

This paper provides a review of existing and developing practices in low-carbon highway construction and near-zero carbon operation strategies, and indicates how they can be used to decrease the carbon footprint of highway infrastructure. It is about the identification of the major innovations, evaluation of their effectiveness, and an outline of the gaps in the research that need to be closed to get really sustainable highways. Through this review, it is expected that the knowledge base necessary for the design, development, and implementation of highways to facilitate the global move towards a low-carbon future will be added by analyzing both the technological, environmental, and economic aspects of the technology involved^[1,10,11].

2. Lifecycle Framework for Carbon Emissions in Highway Infrastructure

Highway infrastructure involves a number of stages, the construction of which adds to the total carbon emissions of the construction, usage, and final dismantling of roads. In order to correctly comprehend and minimize the carbon footprint of highways, a lifecycle approach that considers the emissions at all life cycles is necessary. A lifecycle approach does not only look at the construction stage, but also takes into consideration the continued operation and maintenance, as well as the end-of-life stage, so that any total carbon effect is taken into consideration^[12]. The carbon emissions associated with various stages of highway development, from material production to operation, are summarized in **Table 1**, highlighting the significant impact of operational traffic emissions. The distribution of carbon emissions across different phases of a highway's lifecycle is illustrated in **Figure 1**, emphasizing the significant contribution of operational traf-

fic emissions. This part gives a comprehensive description of a lifecycle diagram of highway infrastructure, the insights into the points of the highest emissions, how the latter are measured, and the necessity of controlling the emissions at every level^[13,14].

2.1. Overview of Lifecycle Phases Relevant to Highway Infrastructure

Highway infrastructure has a lifecycle that is normally several decades in the process; emissions at different stages are experienced. The normal lifecycle framework of assessing the environmental impacts of products and infrastructure, including the highways, has been defined by the International Organization of Standardization (ISO 14044). The key stages of the highway infrastructure lifecycle are the following^[15,16].

2.1.1. Material Extraction and Processing

This stage entails the mining and refining of raw materials that form part of highway construction, like aggregates, cement, steel, bitumen, and other additives. The environmental effect of this stage is a matter of great concern, as it requires the nature and amount of the materials obtained and the energy consumption of the processing procedures. An example is the manufacture of cement, which is among the key materials employed in the construction of roads, and contributes to about 5–6 % world's CO₂. On the same note, the production of steel and bitumen equally comes with high emissions, which are mainly caused by the fact that the production process of these products consumes a lot of energy^[5,17].

2.1.2. Transportation of Materials

Materials must be carried by truck to the construction sites after extraction and processing. The distance travelled, the mode of transportation (road, rail, or sea), as well as the number of materials that are being transported, affect transportation emissions. Firstly, emissions are normally measured by fuel consumption and transportation distance. The transport emissions may be reduced through local sourcing of materials or by ensuring that the transport logistics and routing are optimized^[18].

Table 1. Comparison of Carbon Emissions from Different Highway Construction Phases.

Phase	Emissions Source	Approximate Carbon Emissions (kg CO ₂ e per km)
Material Production	Cement, Steel, Asphalt Production	1,200–3,000
Construction	Construction Machinery (Diesel Equipment)	500–1,500
Operation (Vehicle Emissions)	Fuel consumption, traffic congestion	6,000–8,000
Maintenance	Resurfacing (Asphalt Production, Machinery Usage)	300–1,200
End-of-Life	Demolition, Waste Management	100–500

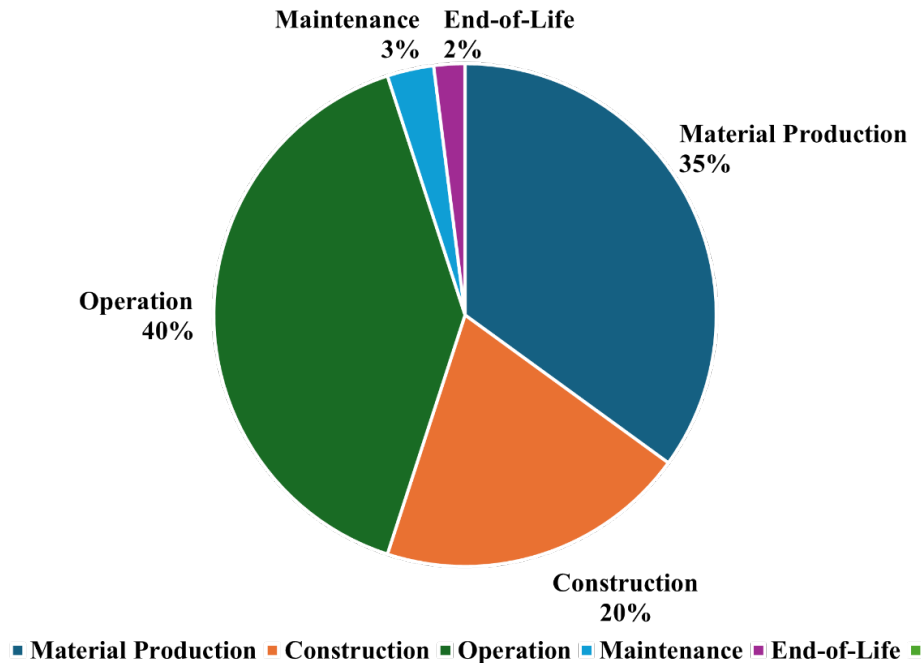


Figure 1. Lifecycle Carbon Emissions of a Highway Project.

2.1.3. Construction/On-Site Activities

This stage will encompass all works associated with the physical construction of the highway, including earthworks, foundations, and asphalt laying, concrete pouring, and the assembly of structural work (bridges, tunnels, and barriers). It also involves the use of construction equipment, which can either be fueled by fossil fuel, which also has a substantial impact on the carbon footprint of the construction process, but also a major source of emissions is the construction machinery itself, particularly in the case of older equipment powered by fossil fuels^[19].

2.1.4. Maintenance and Repair

During its years of operation, a highway must be serviced after some time through laying new tarmac, patching, and reconstruction. The maintenance phase is frequently associated with the use of materials that have a carbon foot-

print (e.g., hot-mix asphalt, bitumen). Remedial measures like repaving a road or changing some components of the structural features add to emissions. The rate and way in which the maintenance is delivered, and also the nature of the low-carbon alternatives used in the repair, influence the total highway system emissions^[20].

2.1.5. Operation

This phase refers to the actual use of the highway by vehicles. Operational emissions come primarily from vehicle exhaust gases, with significant contributions from fuel consumption. Emissions depend on factors such as traffic volume, vehicle types, fuel efficiency, and traffic flow (e.g., congestion or idling). Advances in road technology, such as the integration of electric vehicle charging infrastructure and efficient traffic management systems, can help minimize operational emissions, contributing to the decarbonization of the highway system.

2.1.6. End-of-Life/Demolition and Recycling

The materials that are used in the road are demolished, repurposed, or recycled at the end of the useful life of the highway. The energy needed in the process of demolition, transportation, and material processing gives rise to emissions at this stage. In one instance, asphalt and concrete can be recycled, which would help save carbon emissions because of the raw material requirement. End-of-life planning in most contemporary projects incorporates the option of recycling/reusing much of the material, including reclaimed asphalt pavement (RAP) and concrete aggregates, which can considerably decrease the ecological impact of the demolition^[21].

2.2. Emission Hotspots in Each Phase

In order to prioritize the activities that can be undertaken to minimize emissions, the hotspots in every stage of the lifecycle must be identified. This is where the greatest carbon emissions take place, and hence the best places to target the intervention.

The industrial activity that contributes most to the emissions in this stage is cement production. Cement production emits CO₂ when limestone is calcined, and the general energy-intensive production of cement complicates this issue. Production of steel and asphalt also contributes significantly. Steel, which is commonly employed to reinforce concrete, is energy-consuming, and asphalt, which is paved on the highway, releases plenty of emissions because of the heating that may be necessitated during the mixing of the mixture with aggregates^[22].

Although transportation is not as rich in emissions as material extraction, it may still have a substantial impact on the total carbon footprint, particularly in cases where long distances are to be covered or fossil fuels are the major source of energy for transport vehicles. Truck transportation of goods over long distances and the fuel expenditure can contribute significant emissions if materials have to be obtained over a very long distance.

Construction machinery emissions are a large proportion of this stage of emissions. Excavation, paving, and material handling equipment that is powered by diesel is especially carbon-intensive. Furthermore, the processes entail the emission of energy-consuming methods like heating

bitumen to make asphalt. Although the choice of materials and the method of construction are important factors, the efficiency of the construction equipment is also significant^[23].

Emission also comes with regular maintenance work like asphalt resurfacing, especially when high-temperature asphalt mixes are employed. Mitigation of the emissions can be achieved through the use of low-carbon alternatives, such as warm-mix asphalt. Another reason is the frequency of repair, as the more frequent the intervention, the more materials and energy are used, and the carbon footprint may be further increased.

Vehicle traffic is mostly related to operational emissions. The traffic volume, type of vehicles sharing the road (conventional internal combustion engine vehicles and electric vehicles), and the systems of traffic management can affect the carbon intensity of this stage. Automated traffic systems and electric vehicles (EVs) play a key role in mitigating emissions when the electricity is obtained through renewable energy sources^[24].

Recycling of the materials of an old highway is a major factor that defines the emissions at this point. As an example, reclaimed asphalt pavement (RAP) in reuse in new asphalt mixes lowers the amount of virgin materials required and therefore minimizes the number of emissions by extracting and transporting materials. The additional emissions may also be brought about by the demolition processes that make use of heavy machinery, but in most cases, they are usually lower compared to the construction stage^[25].

2.3. Importance of Full Lifecycle Thinking

It is important to adopt a full-lifecycle view when trying to learn the total carbon footprint of highway infrastructure. Whereas during traditional emphasis has been on emissions during the construction stage, during the long-term life of a highway, the operational emissions may be of more importance. An example is highways constructed using materials that contain a lot of carbon, like cement, which might experience high initial embodied emissions, but their operational emissions through vehicle traffic might exceed these with time. The assessment layer (LCA, carbon accounting, and multi-criteria evaluation) provides the feedback mechanism that closes the loop between performance monitoring and design/procurement decisions (**Figure 2**).

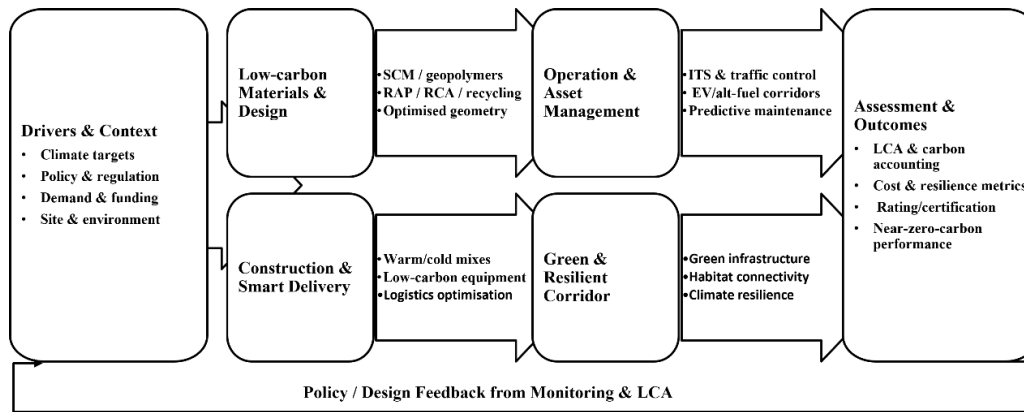


Figure 2. Integrated framework for green and near-zero-carbon highways.

The framework links external drivers (climate targets, policy and regulation, demand and funding, and site/environmental conditions) to four interacting strategy pathways: (i) low-carbon materials and design, (ii) low-carbon construction and delivery, (iii) near-zero-carbon operation and asset management, and (iv) green and resilient corridor functions. Lifecycle-based evaluation (LCA/carbon accounting, cost–resilience metrics, and certification/ratings) translates monitoring and evidence into feedback that informs subsequent design, delivery, and policy updates.

A construction phase can also contribute to a great reduction in emissions by the use of low-carbon construction materials like low-carbon cement and asphalt recycling. Nonetheless, a net-zero target would need a comprehensive solution that is also efficient in terms of highway operation and maintenance. Reduction of operational emissions through technologies, including intelligent traffic management systems, electric vehicle infrastructures, and green road pavements, should be incorporated in highway design.

When considering all phases of the highway lifecycle, we will be able to find more of these areas of reducing emissions, including reusing construction material, moving traffic in an ideal way to avoid traffic congestion, or switching to using electric construction equipment. This overall strategy also highlights the significance of policy frameworks with a lifecycle carbon accounting to ensure that reductions in emissions are both short-term and long-term^[26].

2.4. Challenges of Lifecycle Assessment in Highway Infrastructure

Along with the advantages of lifecycle thinking, there are some issues relating to the application of lifecycle think-

ing to highway infrastructure. Lifecycle assessment (LCA) methods of highways are still under development, and there is currently no comprehensive data on the long-term performance and carbon performance of the most innovative materials. Additionally, the emission factor regional differences (e.g., varying electricity grids, fuel origin, and methods of extracting materials) also make the global implementation of these structures difficult. The fact that traffic patterns and maintenance cycles of various highways vary also makes it harder to evaluate operational emissions. In this connection, the necessity of the specific LCA approaches that consider local conditions, traffic flows, and materials emerges^[27].

3. Low-Carbon Construction Materials & Technologies

The process of switching to low-carbon highways will need a structured change in materials and technologies during the construction stage. Since the embodied carbon of materials is commonly a significant part of the total carbon footprint of highway infrastructure, the use of low-carbon construction materials is essential to reduce the effects on the environment. As shown in **Table 2**, a variety of low-carbon materials, including alternative cements and recycled asphalt, offer substantial reductions in carbon emissions compared to traditional materials used in highway construction. It is this area that provides an in-depth analysis of next-generation low-carbon construction materials and technologies that can be used to revolutionize the highway construction process, greatly lowering the emissions released in the construction process but without degrading the durability, functionality, and safety levels^[28,29].

Table 2. Overview of Low-Carbon Construction Materials for Highways.

Material Type	Carbon Reduction Potential (%)	Durability/Performance	Application in Highways
Low-Carbon Cement (Geopolymers)	40–80%	High (Laboratory tests; field performance TBD)	Pavements, Bridges
Recycled Asphalt Pavement (RAP)	30–50%	High (Proven in long-term use)	Pavements, Resurfacing
Warm-Mix Asphalt	10–30%	Moderate (Research ongoing)	Road paving, Surfacing
Recycled Concrete Aggregate (RCA)	20–40%	Moderate to High (Varies with region)	Base layers, Subbases

3.1. Low-Carbon/Alternative Cements and Binders

Cement production is among the construction processes with the highest carbon content, which contributes to about 5–6 % of the total emission of CO₂ to the world. The manufacturing of ordinary Portland cement (OPC) is also energy-consuming because of not only the calcination of limestone (which generates CO₂) but also the high-temperature kilns used to manufacture cement. Therefore, minimizing the carbon footprint of cement is a major priority of the low-carbon construction efforts on highway roads. Alternative binders and low-carbon cement are presented as a promising measure to mitigate carbon-related emissions generated by cement production. Supplementary Cementitious Materials (SCMs): Portland cement could be partially substituted by fly ash,

slag, silica fume, and natural pozzolans in concrete, and this drastically decreases the amount of carbon that would be produced during cement manufacturing. An example of this is fly ash, which is a byproduct of burning coal, and it has been used successfully as a cement replacement, as it cuts down the amount of CO₂ emissions by up to 30–40% in concrete mixtures. These inorganic polymers are all termed geopolymers and are formed by treating alumina-silicate materials with alkaline solutions. These cements have the ability to attain similar or better strength qualities as OPC with a 40–80% reduction in CO₂. They have been considered in the construction of highways for both pavements and structures. As shown in **Figure 3**, the use of low-carbon materials such as geopolymer cements and recycled asphalt leads to a significant reduction in carbon emissions compared to traditional materials like Portland cement and virgin asphalt^[30–32].

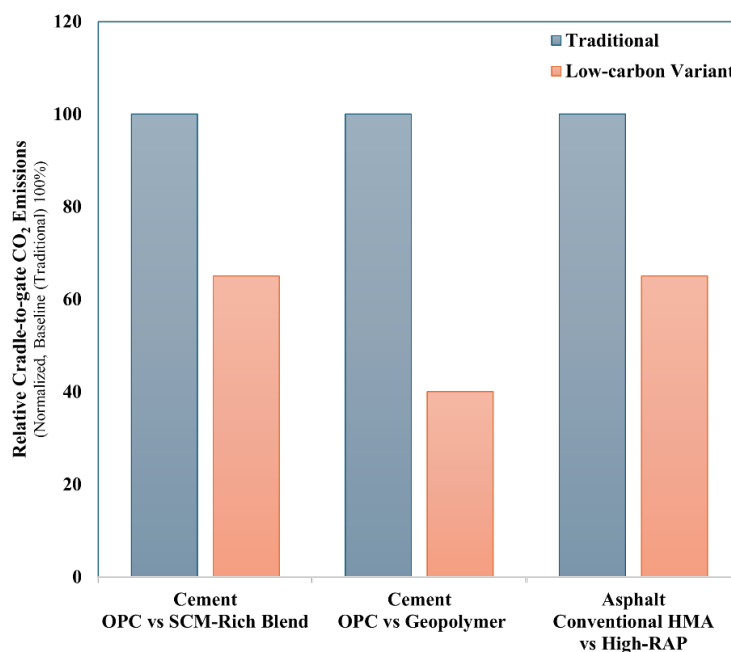


Figure 3. Relative cradle-to-gate CO₂ emissions for selected traditional materials (baseline = 100) and corresponding low-carbon variant.

Note: Low-carbon values are derived from the percentage reduction ranges, using approximate midpoints for visualisation.

Calcium Sulfoaluminate (CSA) Cements are a substitute for OPC, which has a reduced carbon intensity in its

manufacturing. They are made with lower temperatures, consume less energy, and are capable of attaining greater

strength within a shorter period to cure, thus are suited to some construction situations like bridge foundations and road bases. Carbon Capture and Utilization (CCU) in Cement Production: New technologies of capturing CO₂ at cement facilities and then turning it into cement (i.e., immobilizing CO₂ into the cement itself) are an emerging solution to further emissions reduction. This may result in the production of carbon-neutral cement in the future, though it is still in the experimental stage^[33].

These materials, when used extensively, together with correct design and construction methods, can contribute substantially to the low-carbon embodied by the highway pavements, bases, and structural elements, making them core technologies in the quest towards low-carbon construction of highways.

3.2. Recycling and Reuse of Materials: Circular Economy for Pavements and Structures

Circular economy is one of the main principles of sustainable infrastructure, as it focuses on reusing and recycling materials to decrease the amount of virgin resources and waste. Several technologies and practices in the construction of highways will support the recycling of materials to cut down carbon emissions, as well as the use of materials. One of the most common materials used in highway construction is asphalt pavement, the recycling of which has become quite a common practice. RAP can also be recycled to be used in new asphalt mixes, thus less fresh aggregates and bitumen are required. Research has established that the addition of up to 50% RAP in new mixes does not greatly affect the performance of pavements, but results in lower carbon emissions by up to 30–40% than that of traditional hot-mix asphalt.

Although RAP is widely promoted as a key lever for reducing embodied carbon, high replacement levels present non-trivial performance risks. The aged binder in RAP is stiffer and more brittle than virgin bitumen, which typically increases mixture stiffness and rutting resistance, but can simultaneously degrade fatigue performance and exacerbate low-temperature cracking. Experimental and field studies consistently indicate that mixtures with very high RAP contents (on the order of ≥ 40 –50% by mass) are prone to earlier cracking under repeated loading or in cold climates unless carefully mitigated through softer base binders, rejuvenators, or rigorously optimized gradation and volumetrics. If

such durability penalties shorten service life or necessitate more frequent maintenance and rehabilitation, the nominal embodied-carbon savings at construction can be substantially eroded, or even reversed, at the lifecycle scale by additional material use, work zone delays, and associated traffic emissions^[34].

Consequently, RAP utilization should be framed as a performance-constrained decarbonization strategy rather than an unqualified environmental benefit. High RAP mixtures require performance-based design and verification (e.g., mechanistic–empirical checks and fracture/fatigue and low-temperature cracking tests) to ensure that structural reliability is not compromised. In many contexts, a moderate RAP content with robust long-term performance is likely to deliver greater net lifecycle carbon reductions than an aggressive RAP level that precipitates premature distress. Future work should explicitly couple LCA with durability and performance modelling across RAP contents, binder grades, and rejuvenation approaches, to delineate the range in which RAP genuinely optimizes both carbon reduction and pavement longevity.

These cold recycling technologies can be used to recycle and reuse the existing asphalt without high-temperature processing, which will save energy and emissions. Secondly, asphalt rejuvenators are also employed to improve the performance of recycled asphalt to enable it to last longer, and resurfacing is not done frequently. The concrete pavements and other road structures can be reused to form new aggregates, where they can be utilized in the base layers or sub-bases. The RCA application would bring a decrease in the need for virgin aggregates, which is very energy- and resource-consuming to extract. In addition, geopolymers-based binders can be combined with RCA in order to create recycled concrete that has reduced carbon footprints.

In addition to the traditional ways of recycling, there are new technologies in urban mining that are dedicated to extracting useful materials, including steel reinforcement, copper wiring, and other industrial by-products, out of the destroyed infrastructure. The result of this process is a decrease in the need for new raw materials and a decrease in the environmental load of the extraction of materials. With these principles of the circular economy incorporated into highway design, it can achieve a considerable reduction in material consumption, reduce emissions, and minimize the environ-

mental impact of sourcing, transportation, and disposal of the materials^[35].

3.3. Geotechnical & Structural Innovations: Soil Stabilization, Lightweight or Composite Materials

Geotechnical engineering and composite materials innovations are another factor that is making highway construction more sustainable. The innovations will be able to minimize the quantity of materials employed in the construction, as well as the ecological footprint of the employed materials. The techniques of soil stabilization, i.e., the geocells or cellular confinement system (CCS) allow the utilization of the marginal or local soil as building material, causing the transport of high-quality aggregates to be decreased. These techniques also enhance stability and durability of the road structure, the number of maintenance and repair operations becomes minimal, and thus helps in reducing emissions in the long run.

Lightweight Concrete and Composite Materials: Lightweight concrete using expanded polystyrene (EPS) beads or other lightweight aggregates is a material with a huge weight reduction that will reduce transportation emissions. Additionally, structural applications such as bridges and barriers can be built with composite materials (i.e., fiber-reinforced polymer (FRP) systems) instead of traditional steel and concrete to provide reduced weight and higher durability as well as fewer raw materials. Geosynthetic or geocomposite pavement technologies are becoming popular. These systems have enhanced durability, less dependence on traditional aggregates, and lighter materials that can sustain environmentally friendly construction practices^[36,37].

These technologies and materials not only cut down the total carbon footprint of the highway infrastructure, but they can also provide durability in the long run, which lessens the number of repairs and resurfacing, which is also a major contributor to the operational emissions.

3.4. Low-Climax-Impact On-Site Construction Practices

Although the choice of low-carbon materials makes a major contribution to reducing emissions during highway construction, the practices that are practiced on-site are also

important. Construction machinery operation, the way materials are assembled, and the source of energy that is used to run these activities could all cause an increased carbon footprint of highway projects. Replacing old diesel-powered construction equipment with electric construction equipment or hybrid construction equipment is one of the most important measures towards minimizing the carbon footprint of highway construction. The control of electrified machines like electric bulldozers, electric excavators, and electric pavers emits zero direct emissions and can dramatically decrease the carbon footprint of the construction site. By using renewable forms of energy like solar panels or wind turbines to run construction operations, the dependence on fossil fuels can be minimized, and this will result in a decrease in the number of emissions caused by construction activities. This is more applicable to high-energy processes like asphalt production and concrete mixing, where the energy requirements can be high. The carbon emissions caused by the on-site construction activities can be minimized through minimizing the wastage of materials, optimization in transportation and delivery of materials (through the use of just-in-time delivery systems), and through the reduction of soil disturbance. The lean construction concepts can also be utilized to enhance efficiency, save on energy consumption, and decrease the amount of waste generated in the construction process. Here, the fact that 3D printing and modular construction are applicable to highway elements (bridge parts, road barriers, etc.) can highly contribute to a reduction in material waste and construction time, which will result in decreased emissions. The additive manufacturing methods allow applying an exact quantity of the material, which minimizes overproduction and waste^[31,38,39].

These low-carbon construction methods will be necessary to mitigate the environmental effects of the construction stage, meaning the highway infrastructure sector would be in line with the overall sustainability objectives. Decreasing carbon footprint in construction materials and technologies is one of the pillars of the approach to constructing sustainable and green highways. Other new technologies that can be used to cut down on the carbon footprint of highway construction are alternative cements, recycled materials, soil stabilization technology, and lightweight composite materials. These inventions, added to the electrified construction machinery and the sources of renewable energy, provide great poten-

tial to cut down the emissions in the construction process and still retain the strength, endurance, and usefulness of the contemporary highways. With the adoption of a circular economy strategy, resource recovery, and the adoption of smart construction methods, the highway industry can drastically lower its impact on the environment and transition to a more sustainable future^[40–42].

These low-carbon technologies are not only less damaging to the environment in relation to the construction of highways, but their benefits can also be used in terms of long-term operation costs, in terms of the necessity to spend less on maintenance and durability. With the prevalence of such materials and technologies, it is projected that the highway sector would be instrumental in addressing the global carbon reduction goals, which would lead to a low-carbon economy.

4. Near-Zero Carbon Operation & Maintenance Strategies

Highway construction is environmentally friendly by minimizing the carbon footprint by using low-carbon materials and innovative tools; however, to approach near-zero carbon highways, the aspect of the holistic approach needs to be reflected not only during the construction stage but also through the maintenance and disposal of airport constructions and infrastructure. Operation and maintenance of highways can also be significant contributors to the total lifecycle carbon emissions of a highway, and can sometimes be a large proportion of the total emissions throughout the lifecycle compared to highway construction. As such, the long-term sustainability and carbon neutrality of the transportation infrastructure should be enabled by the realization of near-zero carbon operation and maintenance.

In this part, we are concerned with the measures that can be used to minimize carbon emissions during highway operation and maintenance stages. These measures are traffic management, the use of low-carbon materials during repair, sustainable maintenance, and the incorporation of smart technologies to maximize performance and minimize the need to undergo maintenance on a regular basis. Also, the possibility of minimizing the operational emissions using electric vehicle (EV) infrastructure and digital monitoring will be discussed^[1,11].

4.1. Importance of Operation and Maintenance in Lifecycle Carbon Emissions

The most commonly recognized is the embodied carbon in construction materials; highways are long-term infrastructures, which demand decades of operation and maintenance. When they are in operation, highways also emit carbon dioxide through vehicle traffic, which could be of great significance in high-traffic channels. Moreover, the maintenance operations per se, including the road resurfacing and repair, also result in carbon emissions because of the material, the energy used in the construction equipment, or the delivery of the material to the site.

Hence, to have a near-zero carbon highway, the emphasis should be laid on minimizing the carbon footprint on the lifecycle of the entire highway, not only during construction. This necessitates a transformation in the mode of operation and maintenance of the highways, and therefore, it is important to implement practices that are more sustainable and less carbon emission-related^[43].

4.2. Smart Traffic Management and Demand Optimization

One of the biggest contributors to operational emissions on highways is the fuel usage of cars. Traffic congestion, stop-and-go, and poor traffic flow cause the use of a lot of fuel and excessive emissions. The application of smart traffic management systems can significantly decrease congestion, enhance the traffic flow, and, accordingly, decrease emissions. Technologies such as smart traffic systems and electric vehicle charging stations, shown in **Table 3**, play a crucial role in reducing emissions from highway operations by improving traffic flow and supporting green mobility^[44].

Smart Traffic Systems (ITS) are devices with high technologies (sensors, cameras, GPS, and data analysis) to monitor and manage traffic in real-time. Optimization of traffic lights, new traffic information to drivers on the road, and flow optimization depending on the traffic situation can resolve congestion and avoid traffic jams, resulting in fewer idling cars and less pollution. To illustrate, the adaptive traffic signal control systems regulate the timing of the traffic lights according to the current traffic flow, which enables vehicles to pass through the intersections with smoother traffic flow without any unwarranted delays. This will help lower

the fuel use and emissions through the reduction of stop-and-go driving. Traffic volume can be managed through congestion pricing, where vehicles are charged a fee to enter some of the high-traffic zones during the peak hours, mainly in the city. Congestion pricing can be used to maintain vehicle congestion by persuading drivers to travel more dur-

ing off-peak hours or alternative routes, which will reduce emissions. Moreover, encouraging carpooling and public transportation as an alternative to single-occupancy vehicles can also lead to a decrease in the total carbon footprint of highway systems, which will be part of the near-zero carbon objective^[45].

Table 3. Smart Infrastructure Technologies for Reducing Highway Emissions.

Technology	Description	Emissions Reduction Impact (%)	Key Benefits
Adaptive Traffic Control Systems	Dynamic adjustment of traffic signals to optimize flow	5–15% reduction in congestion emissions	Reduced idle time, improved traffic flow
EV Charging Stations	Infrastructure for charging electric vehicles	10–50% reduction in operational emissions	Encourages EV adoption, reduces fuel consumption
Smart Pavement Sensors	Sensors to monitor road condition and traffic flow	2–5% reduction in maintenance emissions	Optimizes repair scheduling, reduces unnecessary work
Electric Construction Equipment	Use of electric-powered machinery for road building	50–100% reduction in construction emissions	Reduces diesel usage, lowers noise pollution

One of the most valuable developments in terms of minimizing the carbon footprint of transportation is the growth of electric vehicles (EVs). The EV charging infrastructure can be installed on highways with fast-charging stations on major routes to promote the mass adoption of EVs. This unification of green mobility strategies promotes the move towards the replacement of fossil-fueled cars, which results in a decrease in the emitted operational level. EV charging infrastructure should be part of highway planning to make sure that EVs can go over long distances without worrying about whether a place to charge exists, thus encouraging the use of zero-emission vehicles. Besides curbing emissions, which are caused by the operation of vehicles, EVs can also curb the carbon footprint of highways, provided they are powered by renewable energy sources, e.g., wind or solar energy.

Even though smart pavement technologies have apparent advantages of traffic monitoring, predictive maintenance, and emissions reduction, the placement of electronic sensors in asphalt or concrete may present some environmental challenges at the end of the pavement life cycle, especially when it comes to recycling and rehabilitation. Otherwise, these components may end up as electronic waste or may pollute the recycled products. In order to address these dangers, new design methods have focused on modular, recoverable sensor architectures, such as in special layers or removable enclosures to allow the extraction of the sensor during milling or rebuilding, inert encapsulation, and low-toxicity materials. Separated using a focused recovery or mechanical screening

approach, targeted at embedded sensors, is in line with existing pavement recycling methods. The emissions saved and reduced by enhanced traffic flow, optimized maintenance, and extended pavement service life can exceed the environmental impacts of sensor incorporation in the lifecycle requirement of carbon assessment and pavement management systems, when lifecycle environmental impacts are evaluated specifically in end-of-life management^[46].

4.3. Low-Carbon Maintenance Practices and Materials

The rehabilitation, repairing, and resurfacing of highways as part of their maintenance process can also be a major contributor to carbon emissions. Highways grow old; hence, they usually need frequent maintenance to guarantee safety and performance. But the conventional ways of maintaining roads, which include resurfacing using asphalt that is of hot mix, are energy-consuming and may contribute significantly to carbon emissions.

The adoption of low-carbon asphalt technologies is one of the best concepts for minimizing the carbon footprint of maintenance. An example of a more sustainable alternative to the normal hot-mix asphalt is warm-mix asphalt (WMA). It is also made at lower temperatures, thus saving on energy used to mix it and hence carbon emissions used in production. Another form of asphalt reuse, reclaimed asphalt pavement (RAP), where old asphalt is used in the construction and/or resurfacing of roads, also has a major effect of minimizing the amount of virgin materials used in road construction or in

the resurfacing process, further reducing emissions of carbon. With the introduction of RAP into new mixes, it uses less energy to generate new asphalt, and raw material mining is also minimized^[47].

Cold In-Place Recycling (CIR) is a maintenance method that entails milling and reuse of the existing pavement material without high-temperature processing. This will save energy use and other emissions that are related to conventional asphalt production. In other instances, commonly CIR may be used with cold-mix asphalt, which can also be employed to resurface roads at lower temperatures, which is an even more sustainable solution. With the implementation of these low-carbon maintenance technologies, the highways are able to drastically cut emissions during the maintenance stage, besides increasing the lifespan of the

infrastructure in question and reducing the necessity of new materials.

4.4. Digital Infrastructure and Predictive Maintenance

The introduction of digital technologies in highway maintenance activities is a new chance to enhance efficiency and cut emissions. The monitoring of the state of the roads and optimization of the maintenance schedule is made possible through the use of digital infrastructure, such as Internet of Things (IoT) sensors, smart monitoring systems, and predictive analytics. The integration of smart technologies into highways and their respective emissions reduction impacts is depicted in **Figure 4**, highlighting the role of EV charging infrastructure and intelligent traffic management systems^[48].

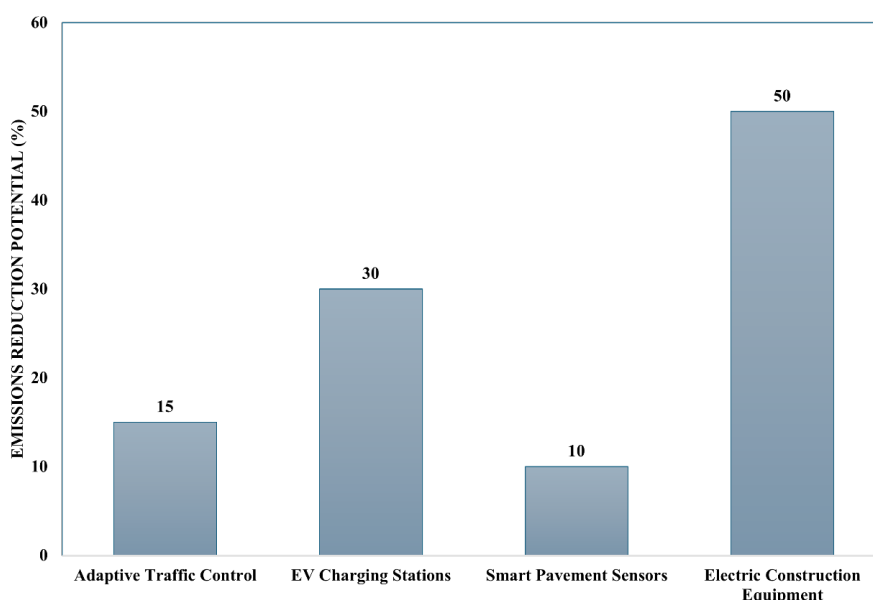


Figure 4. Smart Highway Technologies and Their Emissions Reduction Potential.

Predictive maintenance involves live information from sensors on roads and vehicles to predict when a highway system or part would require repair. This enables easier planning of repair processes to eliminate unnecessary maintenance operations and wastage of resources. Data-driven decisions can be made to implement only the necessary intervention when there is a need to reduce the occurrence of disruption, minimize wastage of materials, and optimize the workforce. To illustrate, sensors in the pavement could be used to measure cracking, rutting, and wear prior to their becoming serious problems, and therefore interventions could be made to prevent the situation, thus avoiding the need to

repair it on a large scale. This will minimize the carbon footprint of the maintenance activities and increase the life of the infrastructure.

Smart pavements (that have sensors and other technologies that check traffic loads and road conditions, and other environmental factors) can also help in emissions reduction during maintenance. These technologies make it possible to collect data, which drives the decision-making process and allows the highway authorities to give priority to repairs and replacements with the help of real-time information. Traffic management systems can also be made with the use of smart pavements that are used in providing valuable informa-

tion that would help to optimize traffic flow, thus reducing emissions even more, on the emissions attributed to traffic congestion and idle time^[48].

4.5. Long-Term Sustainability and Lifecycle Carbon Management

A long-term approach to carbon management is essential in order to have near-zero carbon highways. This entails the use of end-to-end carbon accounting systems which monitor and quantify emissions throughout the lifetime of a highway- both construction and operation, and maintenance. Lifecycle Carbon Assessment (LCA) tools are able to assist highway planners and engineers in considering the overall carbon footprint of a highway during its lifespan. Using LCA in the planning and decision-making processes, policymakers would be able to recognize the opportunities that allow a cut down of carbon emissions at all stages of the highway life cycle, such as operation and maintenance of the highway. As an example, the emissions of the traditional pavement materials may be compared to those of low-carbon materials, and the carbon footprint monitoring will allow making more sustainable decisions in the context of construction and maintenance^[49]. Where emissions are inevitable, the carbon offset programs can be adopted to offset the amount of carbon emitted in the operation and maintenance of the highways. Such offsetting initiatives may incorporate forest planting, reforestation initiatives, and spending on renewable energy initiatives that will counter the carbon emissions generated by highway activities^[50].

4.6. Achieving Near-Zero Carbon Highways through Operation and Maintenance

Achieving near-zero carbon highways requires a comprehensive approach that spans beyond construction to address the emissions generated during operation and maintenance. By integrating smart traffic management, promoting the use of electric vehicles, and adopting low-carbon materials and innovative maintenance practices, it is possible to drastically reduce the carbon footprint of highway infrastructure. Additionally, the adoption of digital technologies and predictive maintenance systems will help optimize operations and reduce unnecessary emissions from repair activities. As the transportation sector continues to evolve towards sus-

tainability, the transition to near-zero carbon highways will play a key role in meeting global climate goals and promoting a more sustainable future for transportation infrastructure^[10].

5. Green Infrastructure and Ecological/Environmental Integration

Green highways development transcends the scope of carbon emissions that come with the construction and operation of roads in the context of sustainable infrastructure. The green infrastructure concept incorporates ecological aspects in designing, building, and running of highways, thereby increasing the biodiversity and promoting environmental sustainability and climate change resilience. This discussion examines how green infrastructure can play the role of developing environmentally integrated highway systems that not only reduce carbon emissions but also lead to a positive contribution to local ecosystems and communities^[51].

5.1. Defining Green Highways: Beyond Low-Carbon Construction

The green highway is a term used to describe roads and highways that have been developed, built, and maintained considering environmental sustainability as the main focus. Although a significant part of the present attention towards the development of highways is the minimization of carbon emissions, the larger concept of green highways covers other aspects of system services, climate stability, and biodiversity improvement. A green highway is developed through proper planning to prevent areas that are ecologically sensitive, e.g., wetlands, forests, wildlife corridors, etc., so that development of the roads does not interfere with the local natural ecology or contribute towards habitat fragmentation. It also requires the provision of features that favor or protect the local habitats, such as wildlife overpasses, underpasses, and green corridors through which species may move between broken landscapes. Adopting new stormwater management facilities that minimize run-offs, enhance water quality, and safeguard local water bodies. Lessening construction disturbances by noise-reducing measures, reducing soil erosion, and dust pollution control^[52,53].

A green highway combines the above factors, incorporating both environmental conservation and carbon reduction. Green highways are also open to the holistic approach to en-

environmental sustainability by taking into account the greater environmental impact of highway infrastructure, which acknowledges the significance of ecosystem health in conjunction with carbon emission reduction.

5.2. Integrating Ecological and Environmental Considerations in Highway Design

The integration of ecological principles into highway design involves prioritizing the protection of biodiversity and the restoration of natural habitats within the infrastructure's footprint. Several key strategies can help integrate ecological considerations into highway projects:

5.2.1. Wildlife Corridors and Habitat Connectivity

The care and improvement of habitat connectivity is one of the most significant ecological characteristics of green highways. Roads may also serve as obstacles to the movement of living things, disrupting habitats and migration patterns. With the introduction of wildlife corridors, overpasses, and underpasses, wildlife is able to cross highways without danger, resulting in mortality due to road accidents, as well as allowing populations to exchange genes between isolated populations. These structures prevent the adverse impacts of roads on biodiversity and are also part of the resilience of the ecosystem as they enable species to migrate across fragmented habitats. An example of this would be the use of wildlife overpasses (elevated highways, bridges) to facilitate the movement of animals, which have been used in several countries, including Canada and the United States, where large mammals (deer, bears, and moose) have been able to cross the roads safely. Likewise, underpasses that are smaller species such as amphibians, reptiles, and insects are used to mitigate the barrier caused by highways on the local population of wildlife^[54,55].

5.2.2. Green Corridors and Habitat Restoration

Along with wildlife passages, green corridors can be used along highways that act as buffer strips that promote native plants and local wildlife as well. These strips may consist of native plantings, restoring wetlands, and introducing pollinator habitats, which will help the biodiversity and make the climate resilient. The aesthetic and recreational value of green corridors to communities also ensures that

there is space where people can do their outdoor activities, and also boosts urban environments. Moreover, highway projects may also include habitat restoration plans that may involve the replantation of native trees, shrubs, grasses, etc., which may assist in restoring the regions that might have been disrupted in the course of the construction works. These rehabilitated habitats contribute to the enhancement of biodiversity, as they sustain a wide range of species, including important ecosystem-performing species, such as pollination and pest control^[56].

5.2.3. Integrating Vegetation in Road Design

The vegetation is also used in the development of green highways. Highways could also serve as carbon sinks by using the green infrastructure to capture CO₂, thus purifying the air, by integrating green infrastructure into the road design. An example is tree-lined streets and vegetated embankments, which can be used to alleviate the urban heat island effect, minimize noise pollution, and enhance air quality by trapping the particles and CO₂. Plants and trees also serve to manage storm water through incorporation in designing highways, since the trees and plants reduce the water runoff and increase water seepage. Sustainable water management can also be enhanced by the use of permeable pavements and bioswales (vegetated ditches that filter stormwater) that will limit the amount of stormwater that flows into water bodies and also filter out the pollutants before they reach water bodies. These natural systems offer affordable and ecologically suitable options to the conventional management of storm systems like underground pipes or concrete courses^[57,58].

5.3. Stormwater Management and Water Quality Protection

Stormwater runoff is considered one of the biggest environmental issues brought about by highway infrastructure. Roads and highways bring about impervious surfaces, causing water to fail to enter the soil naturally, resulting in a high level of surface run-off, erosion, and contamination of the water in the surrounding areas. The contaminants, including oils, heavy metals, and debris, are also often carried to rivers and streams via highways. To alleviate the above challenges, the green highways can be designed using novel stormwater management methods, i.e., bioswales, which are ornamental features that slow down the flow of stormwater and filter

the water to minimize the quantity of the water and enhance the quality of the water. Porous or permeable pavements enable water to filter into the surface, decreasing the runoff and enhancing groundwater recharge. In practical cases, the recreation of wetlands along highways can be used to trap and treat stormwater before it flows into the nearby water bodies. Surface runoff is minimized by shallow, vegetated stormwater-absorbing areas, which offer ecological benefits by providing habitat to pollinators. These techniques will enable highways to have a considerably lower impact on the local waterways and enhance the quality of water and ecological wellbeing in the local ecosystems^[59,60].

5.4. Climate Resilience: Adapting Highways to Changing Conditions

Climate change poses great problems in the infrastructure, among them being a high risk of floods, erosion, and extreme temperatures. Natural infrastructures and adaptive designs can be incorporated in order to make green highways more resilient to these challenges. To illustrate, one can mitigate the threat of the damage that may occur due to heavy rainfall and flooding by restoring natural floodplains or designing highways to handle floods. Flood-prone areas can be fitted with high roads or flood-resistant materials, which may save the infrastructure and ensure that it does not become useless in the event of extreme weather. Highway construction with drought-resistant plants and trees can be used to keep the green infrastructure intact even during periods when there is a lack of water or during heat stress. Through preemptive actions against the effects of climate change, green highways can make the transportation infrastructure resilient and, at the same time, bring about positive effects to the environment and the local population^[61,62].

5.5. Social and Community Benefits

Besides benefits for the environment and ecology, green highways have a high degree of social benefits. Green spaces, wildlife corridors, and more effective stormwater management systems can be integrated to produce more visually pleasing roadways, which contribute to the augmentation of the quality of life of local communities. Indicatively, green infrastructure has been found to benefit the mental health of the community, offer recreational space, and of-

fer better air quality, which leads to healthier communities. Green highways have the potential to raise property values in the surrounding areas, bring about tourism, and provide local employment in the green economy, including landscape design and ecological restoration. Engaging the local communities in the planning and maintenance of green highways will provide community ownership and also make the project conform to the local needs and values. Such projects can help make the urban and rural environment more equitable and sustainable by incorporating social factors in green highway design^[63].

5.6. The Role of Green Infrastructure in Sustainable Highway Development

Green infrastructure is a radical concept of highway design that incorporates ecological, environmental, and social aspects in the construction and use of roads. Green highways make land-use decisions to address the challenges of traditional highway infrastructure on the environment through increased habitat connectivity, biodiversity, water quality, and resilience to climate change. Designing highways with green infrastructure is a necessary move in the attainment of net-zero carbon and making transportation infrastructure supportive instead of harmful to planet health, as governments and industries shift to more sustainable transport systems. Not only is incorporating ecological values in the development of a highway a moral duty, but it is also a practical need in the environment, where the climate is shifting at a very fast rate^[64-66].

6. Quantitative Assessment, Carbon Accounting, and Evaluation Frameworks

As the pressure on sustainable infrastructures mounts, a greater need to measure and make accurate evaluations of the environmental impacts of highway projects. Quantitative assessment and carbon accounting are the keys to minimizing the environmental footprint of transportation infrastructure, such as highways, which helps to orient the process of heading towards near-zero carbon emissions. Not only do these tools establish the level of carbon emissions that occur during the lifecycle of a highway, but they also

advise on what materials, technologies, and practices can be adopted to reduce climate change^[10].

One of the most important steps of carbon assessment is the definition of boundaries of the system, where specific processes, activities, and emissions are outlined that are to be included in the analysis. In the case of highways, system boundaries can encompass construction and material production, maintenance and operational activities, or even Land Use Change (LUC) emissions, including deforestation, soil disturbance, or wetland conversion to construct highways. Additionally, the auxiliary operational energy can be included, such as street lighting, tunnel ventilation, and traffic management systems, which may or may not be included depending on the scope of the study. It should be noted that various definitions of boundaries may result in significantly different outcomes of the assessment, influencing the overall carbon footprint and the definition of the main mitigation measures.

In this section, the study examines the methodologies, problems, and models of the carbon emissions of highways that focus on properly clarified system boundaries. The combination of the Lifecycle Assessment (LCA) with the carbon accounting and sustainability assessment frameworks will allow decision-makers to single out the interventions that can help mitigate emissions and promote the construction of low-carbon highway infrastructure^[67].

6.1. Overview of Lifecycle Assessment (LCA) for Highway Infrastructure

Lifecycle Assessment (LCA) is the notion behind carbon accounting, which determines the environmental impact of a product, system, or project by summing up the extraction of raw materials to the ultimate discarding of the item. In a highway scenario, LCA allows stakeholders to identify the carbon footprint in all the life cycles of a highway, such as construction, operation, maintenance, and decommissioning.

One of the most important processes in LCA is system definition, which is a measure of what processes, activities, and emissions should be incorporated in the assessment. In highway projects, the system boundaries can be material production, transportation, construction, maintenance, and operation, and Land Use Change (LUC) emissions of activities like deforestation, soil disturbance, or wetland conversion. Also, there might be auxiliary operational energy usage,

which includes street lights, tunnel ventilation, and traffic management infrastructure, depending on the extent. Boundary definitions may play a major role in determining the outcome of an assessment, including the overall carbon footprint of the process, and which mitigation measures should be prioritized^[68].

Defining the scope and objectives is the initial step of LCA that involves the system boundary and materials, activities, and processes that should be taken into account. After the scope has been established, inputs and outputs are measured to create an inventory, which is a list of raw materials, energy utilization, construction machinery emissions, and, where available, LUC and auxiliary operational energy emissions.

This is followed by the assessment of the possible environmental effects of these inputs and outputs. Although the main attention should be paid to CO₂ emissions, other aspects of the environment also have a chance to be involved. The last thing will be the interpretation of the results and the possibility of determining the primary sources of emissions and improving opportunities. As an illustration, LCA can show that steel or cement production causes the most significant share of emissions, which implies that the carbon footprint can be significantly decreased by using low-carbon alternatives like geopolymers cements or recycled steel. Equally, emissions during the operation of vehicles on the highway are a potential huge factor, and this means that mechanisms such as the promotion of electric cars or the optimization of traffic may lead to a reduction in the operational emissions.

It is this integrated and place-based perspective that makes LCA a complete picture of the environmental effect of a highway project, which allows planners and policymakers to make sound decisions that would facilitate the development of low-carbon infrastructure^[69,70].

6.2. Carbon Accounting for Highway Projects

Although the macro view of environmental effects is offered by means of LCA, carbon accounting is concerned with the direct quantification and tracking of the carbon emissions during the lifecycle of a highway. Carbon accounting is a process of adding up the CO₂ emissions from all activities related to a highway project, like the production of materials used in the highway project, the construction, operation, and maintenance.

One of the most important issues in carbon accounting is the definition of the boundaries of the system, that is, what emissions are counted in the assessment. In the case of highways, such limits may include construction materials (asphalt, cement, steel), construction equipment, material transportation, and construction site activities, operation emissions by vehicles, auxiliary energy use (e.g., street lighting, tunnel ventilation), and Land Use Change (LUC) through deforestation or soil disturbance. The boundaries are of vital importance since their selection can lead to radically varied carbon accounting results^[71].

Carbon accounting helps to measure the operational emissions that, in most cases, constitute the biggest part of the overall carbon footprint of a highway. Operational emissions may be estimated according to the flow of traffic, the type of vehicle, fuel consumption, and efficiency, and may be minimized through such interventions as the promotion of electric cars or the introduction of smart traffic systems that are more efficient in the optimization of traffic flow and decreased fuel consumption.

Also, the carbon accounting applies to the emissions relating to the maintenance and repair processes during the lifetime of the highway, such as the resurfacing process, heavy machinery operation, and transportation of materials. Incorporating such activities into the system boundaries, it may be possible to find more ecologically friendly options, e.g., warm-mix asphalt, which has lower energy consumption than hot-mix asphalt, or cold in-place recycling, which leaves the production of a new material to a minimum. Emission factors are another key instrument in carbon accounting as they are used to estimate the CO₂ emission of individual materials, processes, or operations. An example is to determine the carbon footprint of concrete by multiplying the kilograms of cement used by its emission factor, or to determine the amount of vehicle emissions by looking at the trends in traffic and the fuel efficiency. Standardized emission factors offer a standard framework of comparison of the emissions between regions and projects, though they might not be accurate based on data availability and regional specificity. With a strict delineation of system boundaries and the introduction of LUC and auxiliary energy where suitable, carbon accounting will be an overall and practical instrument to highway planners and policymakers to determine where emissions hotspots are, the possibilities of mitigation, and

the sustainability of highway projects^[72,73].

6.3. Evaluation Frameworks for Low-Carbon Highways

In order to evaluate the sustainability of highway infrastructure projects, a number of green highway rating systems have been developed. These frameworks offer a holistic collection of standards on the basis of which the environmental, social, and economic effects of highways can be assessed to create a sustainability rating that indicates the degree to which a project will meet these standards.

The proper definition of system boundaries that are applied in these evaluation structures is an important part of the evaluation. An example is that in some systems, the carbon footprint element of a rating can cover not only emissions (production of materials, construction, maintenance, and operation of highways), but also possibly Land Use Change (LUC) emissions (such as deforestation) or auxiliary operational energy (such as street lighting and tunnel ventilation). These factors can be influential in the overall sustainability rating, and thus, it is important to have a clear and uniform definition of boundaries across projects^[74].

Green Roads is among the best-known systems of sustainable highway ratings. It compares projects to 12 major criteria, such as carbon emission, materials, energy usage, water management, and ecological impact. Highways may be rated bronze, silver, gold, or platinum depending on their performance. Green Roads offers a more realistic and complete measure of the environmental impact of a project by adding emissions that relate to LUC and auxiliary energy, where necessary.

Another such scheme is the Sustainable Infrastructure Rating System (SIRS), which rates highways based on environmental, social, and economic outcomes. Its requirements entail a cutdown of carbon footprint, water, and biodiversity. The main concern here is system boundaries because the addition of LUC and auxiliary energy in SIRS is such that the evaluation of the environmental impact of highway construction and operation is comprehensive.

These assessment systems assist policy makers, engineers, and developers in embracing best practices in the construction of highways that can be sustainable. Through clear and boundary-sensitive evaluations, they promote the application of low-carbon materials, energy-conserving building

approaches, and operation plans, which eventually lead to a decrease in the carbon footprint of highways^[75,76].

6.4. Sustainability Assessment Tools

Sustainability assessment tools are also software applications that are specific to modeling and assessing the environmental performance of highway projects. These tools combine LCA information, carbon accounting, and other indicators of sustainability to assist engineers, designers, and policymakers in evaluating the effects of their choices on the environment.

One of the key aspects of such tools is that they allow establishing system boundaries, meaning what processes and emissions will be involved in the assessment. System boundaries can include material production, transportation, construction, maintenance, operation, Land Use Change (LUC), and auxiliary operation energy, like in the case of street lighting or tunnel ventilation in the case of highways. These boundaries should be clearly defined, and various options may have a great influence on the outcomes and finding the most important mitigating measures.

SimaPro and OpenLCA, which are very popular tools, enable users to enter data on materials, energy consumption, and transportation to determine carbon footprints and other environmental effects. An example is SimaPro, which is popular in evaluating the environmental performance of construction projects such as highways, and OpenLCA, which is a free software but is largely useful in comparing the sustainability impact of various materials, designs, and forms of construction. Both of the tools facilitate the assessment of the emissions related to LUC and auxiliary energy, assuming the corresponding data are presented in the inventory.

These tools enable dynamic assessment of the carbon footprint of a highway project by incorporating boundary-sensitive LCA, as well as carbon accounting. They help planners and decision-makers to find the areas of high impact, assess mitigation measures, and give priority to the interventions that facilitate low-carbon highway infrastructure^[67,77].

6.5. Challenges and Limitations of Carbon Accounting and LCA in Highways

Although carbon accounting and LCA are indispensable tools for analyzing the environmental impact of highway

projects, they face several challenges and limitations that can affect the accuracy and comprehensiveness of assessments^[75].

A primary challenge lies in data availability and quality. Reliable information on materials, construction processes, emission factors, and operational energy usage may be missing or inconsistent. This is particularly true for new materials or technologies, where emission factors are not yet standardized, or for region-specific data, which may vary widely due to differences in energy sources, climate, or traffic patterns^[75].

Another important limitation is related to system boundaries. The inclusion or exclusion of emissions from Land Use Change (LUC)—such as deforestation, soil disturbance, or wetland conversion—and auxiliary operational energy, such as street lighting and tunnel ventilation, can substantially alter the results of carbon accounting and LCA. In many cases, these emissions are underrepresented or omitted, leading to an incomplete picture of a highway's carbon footprint. Similarly, boundary definitions may differ across projects, regions, or assessment tools, making comparisons between projects challenging^[75].

Highway projects are inherently complex and long-term, with multiple stages that include construction, operation, maintenance, and end-of-life. Monitoring emissions across these stages, especially when including LUC and auxiliary energy, requires robust data collection systems, smart sensors, and real-time monitoring technologies. Without these tools, assessments may fail to capture dynamic variations in traffic, operational energy usage, or maintenance activities^[75].

Despite these challenges, advancements in technology and methodology are improving accuracy. Smart highway technologies, digital infrastructure integration, and real-time monitoring can capture traffic-related emissions, maintenance activities, and operational energy use continuously. Moreover, efforts to standardize carbon accounting systems across regions and industries will reduce discrepancies, improve comparability, and facilitate the inclusion of previously overlooked emissions such as LUC and auxiliary operational energy^[75].

In summary, while data gaps, boundary inconsistencies, and methodological challenges remain, improvements in data collection, monitoring technologies, and standardization will

enable more comprehensive and reliable carbon accounting and LCA, supporting better decision-making and more effective carbon reduction strategies in highway projects^[78,79].

6.6. Advancing Carbon Evaluation in Highway Infrastructure

The development of sustainable, near-zero carbon highways relies on the rigorous evaluation and control of carbon emissions throughout a project's lifecycle. By combining Lifecycle Assessment (LCA), carbon accounting, and sustainability assessment frameworks, the highway industry can identify effective strategies to minimize environmental impacts during construction, operation, and maintenance^[77].

A key area for advancement is the clarity and consistency of system boundaries. Including emissions from Land Use Change (LUC), such as deforestation or soil disturbance, and auxiliary operational energy, such as street lighting, tunnel ventilation, and traffic management systems, ensures that carbon evaluations reflect the full environmental footprint of highway projects. Consistent boundary definitions across projects, regions, and assessment tools will improve comparability and enhance the reliability of sustainability metrics^[77].

Despite the challenges of data availability, regional variability, and methodological complexity, emerging technologies are improving the precision and timeliness of carbon evaluation. Smart sensors, real-time monitoring, and digital infrastructure integration allow continuous tracking of emissions from traffic, maintenance, and operational activities, enabling more dynamic and responsive carbon management^[77].

As additional data become available and new low-carbon materials and technologies are developed, carbon accounting and assessment frameworks will continue to evolve and become more comprehensive. The integration of advanced data collection, standardized regional emission factors, and inclusion of previously overlooked sources such as LUC and auxiliary energy will enable highway planners and policymakers to make more informed decisions, prioritize carbon reduction strategies effectively, and achieve tangible improvements in environmental performance.

In the future, boundary-aware carbon assessment will be a fundamental component of sustainable infrastructure development, allowing highway projects to make a signifi-

cant contribution to global climate objectives and advance toward a low-carbon future for transport infrastructure^[80].

7. Barriers, Challenges, and Research Gaps

Regardless of the major technological progress in the low-carbon technical solutions and plans to build sustainable highways, it is quite complicated to make infrastructure almost without carbon emissions. These obstacles are based on the numerous technical, economic, institutional, and social aspects that impede the popularization of sustainable approaches to highway design, construction, and operation. Besides these issues, some gaps in research and knowledge need to be filled to enhance the feasibility, efficiency, and effectiveness of low-carbon highways. This part is a detailed discussion of these barriers, challenges, and gaps of research, providing insights into what should be overcome to achieve the vision of near-zero carbon highways. The key barriers to low-carbon highway development, along with their corresponding solutions, are summarized in **Figure 5**, providing a visual roadmap for overcoming challenges in the sector^[40,81].

7.1. Technical Challenges

The technical limitation of the existing materials, mechanisms, and technologies is one of the major obstacles that stand in the way of the wide adoption of low-carbon highways. Although several innovative materials and technologies offer potential in minimizing the carbon footprint of highway infrastructure, their performance, durability, and scalability have been a major issue of concern. As presented in **Table 4**, the challenges faced in achieving low-carbon highways, such as high upfront costs and technical uncertainty, can be mitigated through policy reforms and industry collaboration^[82].

7.1.1. Durability and Performance of Low-Carbon Materials

Alternative cements, geopolymers, recycled asphalt, and many other low-carbon materials have significant carbon emission reduction over traditional materials. Nevertheless, there are still doubts about their durability over time and their performance under highway and real-world conditions.

As an illustration, geopolymers cements, with a significantly smaller carbon footprint than conventional Portland cement, have demonstrated good initial performance in the laboratory. Nevertheless, their attitude in traffic congestion, freezing and thaw processes, and extreme conditions must be further con-

firmed with the help of long-term field research. In the same breath, as much as recycled asphalt pavement (RAP) will cut on the use of virgin materials, its durability and resistance to wear as time progresses might not necessarily meet the standards of high-traffic roads^[32,83].

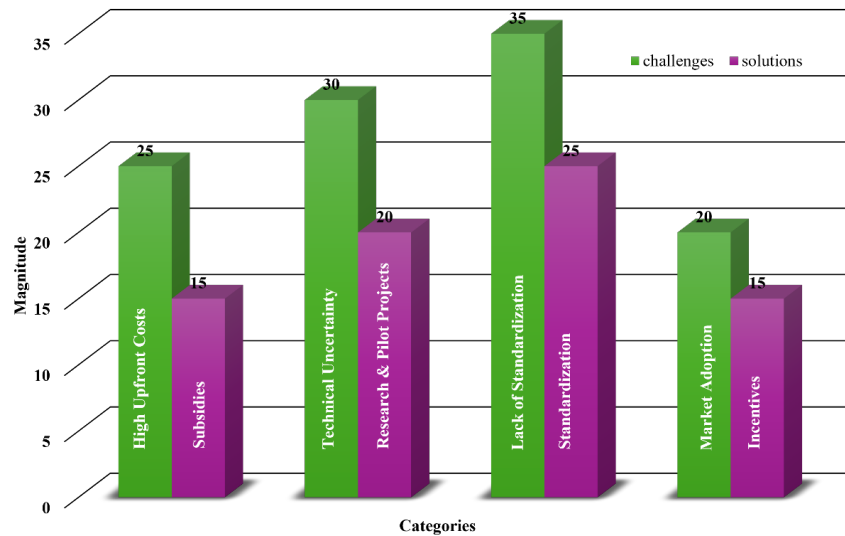


Figure 5. Barriers to Low-Carbon Highways and Solutions.

Table 4. Challenges and Solutions for Achieving Low-Carbon Highways.

Challenge	Description	Proposed Solution
High Upfront Costs	Low-carbon materials and technologies are more expensive initially	Government subsidies, Public-Private Partnerships
Lack of Standardization	Inconsistent regulations and materials standards	Development of global sustainability standards
Technical Uncertainty of New Materials	Durability and long-term performance of new materials (e.g., geopolymers)	Long-term field studies, pilot projects
Insufficient Supply Chain for Recycled Materials	Limited availability and logistics of recycled materials	Investment in recycling infrastructure, better sourcing practices
Resistance to Change in Industry Practices	The construction industry’s slow adoption of sustainable practices	Industry training, incentives for sustainable practices

It is also highly important that these alternative materials are as efficient or more so than traditional materials in order to ensure that the practice of low-carbon construction can be widely adopted. Thus, the prolonged performance and stability of low-carbon materials in different environmental and traffic conditions should be evaluated in further research.

7.1.2. Integration of New Technologies in Highway Systems

Intelligent technologies, including intelligent traffic regulation systems, electric vehicle (EV) charging stations,

and real-time monitoring systems, are not easy to implement into the current highway infrastructure, and the process is resource-consuming. Significant are the technical aspects of implementation of these technologies into the legacy systems, interoperability, and security of the data. As an illustration, smart traffic systems that can be used to optimize the flow of traffic and reduce congestion would need a sound digital infrastructure to keep track of the traffic trends, and this is not easily attained in most areas, especially in developing nations or those in rural areas. Moreover, the deployment of EV charging stations at the highway level involves significant costs associated with the power supply network and the

establishment of uniform charging networks that will serve various types of vehicles. The use of smart highways and the electrification of the overall highway infrastructure are fraught with difficulties in terms of system integration, standardization, and compatibility in the long-term operation^[84].

7.2. Economic and Market Barriers

The economic and market barriers to achieving low-carbon highways are multifaceted and include concerns related to upfront costs, market incentives, and the economics of low-carbon technologies.

7.2.1. High Upfront Costs of Low-Carbon Technologies

The high initial cost is one of the greatest impediments to change towards the introduction of low-carbon construction methods and technologies. Although low-carbon materials and technologies can be beneficial in both the long-term environmental and operational terms, their initial investment can be much greater compared to traditional options. As an example, green technologies like permeable pavements or smart traffic systems, as well as low-carbon cements, may be more expensive in terms of initial capital outlay since research and development costs may be substantial, or raw materials are expensive or require specialized equipment and labor.

As an illustration, the change to an electric construction equipment or the adoption of a modern digital monitoring system, capital investments are also high and may not be viable at a certain point in time for many highway developers or contractors, particularly in resource-limited countries or regions. There is little financial incentive to justify the long-term benefits of sustainable infrastructure projects because the economic constraints of governments and individual contractors in many regions limit the ability of these individuals to justify the long-term impacts of any project^[85].

7.2.2. Market Adoption and Supply Chain Challenges

The other major obstacle to low-carbon highways is the adoption of alternative materials and technologies in the market. Market demand for such solutions can be low because even in cases where alternatives are available with low carbon emissions, there is no awareness or consultation of

the risks that new materials and technologies have. Other supply chain issues include the sourcing of low-carbon materials. As an example, recycled materials like reclaimed asphalt pavement (RAP) or recycled concrete aggregates (RCA) do not necessarily exist in large quantities that are required when a large-scale highway is required, and the cost of transportation of recycled materials like the above may be high. These challenges are enhanced by the absence of a standard market for green materials and technologies. The standardized certifications and regulations play a major role in guaranteeing that these low-carbon alternatives are up to the required standards of quality in the construction of highways^[85].

7.3. Institutional and Regulatory Barriers

The institutional and regulatory conditions also have a key influence on the practicability of sustainable highways. Although there is increasing attention to the problem of climate change and sustainability, there are usually no or insufficient regulatory frameworks and policies that could promote the development of low-carbon highway infrastructure.

7.3.1. Inconsistent Policy and Regulatory Frameworks

Policies and regulations to facilitate the construction of low-carbon highways and their use are either absent or inadequately developed in most areas. Although the adoption of green building codes or other sustainable transportation programs has been undertaken by a few countries and regions, there are still numerous other countries that do not have the regulatory frameworks required to support the large-scale application of sustainable practices. Specifically, it appears that uniformity across jurisdictions does not exist, and various standards, regulations, and incentives ensure the inability of the private sector to make long-term and steady investments in low-carbon infrastructure. Low-carbon projects are not always financially viable due to the lack of financial incentives, including tax credits, subsidies, or public-private partnerships, which are more sustainable. The policymakers should fill these loopholes by coming up with clear and consistent policies that focus on sustainability and, at the same time, provide incentives to the private sector to encourage them to implement low-carbon solutions^[86].

7.3.2. Procurement Practices and Resistance to Change

The construction industry is a traditional procurement process that is usually focused on cost and speed, as opposed to environmental issues. Highway projects are commonly provided to the lowest bidder with no consideration of the environmental benefits in the long term, as well as the life-cycle cost of the materials and technologies used. This acts as a great hindrance to the implementation of low-carbon technologies because the contractors and developers can opt not to use a new solution when it raises the initial cost, despite its long-term benefit. There are also possible institutional obstacles to the proposed change, where it is likely to occur in areas where the current construction industry is predominantly based on traditional materials and construction techniques. To overcome this resistance, not only regulatory changes, but also a change in industry culture to place more importance on sustainability and environmental stewardship is necessary^[87].

7.4. Social and Ecological Trade-Offs

In order to realize low-carbon highways, it is common to make a decision, which implies compromising between the environment and social and ecological factors. Although low-carbon technologies can be used to reduce carbon emissions, they can also influence the social or ecological environment unintentionally, and such effects must be examined^[88].

7.4.1. Balancing Carbon Reduction with Ecosystem Health

Among the most important problems of developing sustainable highways, it is necessary to make sure that the replacement of the carbon-emitting materials and technologies will not harm the local ecosystems. An example of this would be that geopolymers or recycled materials could minimize the carbon footprint; however, when the materials are not procured in a sustainable manner, or there are adverse environmental effects (e.g., contamination of water or disturbance of habitat), the advantages might not be as high as expected. On the same note, the attempts to mitigate emissions, by using energy-efficient construction methods, should also consider the possible effects on biodiversity and the natural habitats, particularly in ecologically sensitive regions^[89].

7.4.2. Community Engagement and Public Perception

Community involvement is very important in the adoption of low-carbon highway developments, more so in cities. New infrastructure projects are frequently opposed in communities because of an expected increase in traffic congestion, pollution, or green cover loss. To resolve these issues and, in the process, preserve the environmental positive effects of sustainable highway development, there must be effective communication between developers, policymakers, and the local populations. Low-carbon infrastructure projects need the backing of the populace so that the objectives of the projects are attained not only in terms of environmental objectives but also social ones.

7.5. Research Gaps and the Need for Further Innovation

Several critical research gaps in the field of low-carbon highways must be addressed to accelerate the transition to sustainable transportation infrastructure.

7.5.1. Long-Term Performance Data

There is a huge research gap in the performance of low-carbon materials and technologies over long periods of use in highways. Although delivery of laboratory research and pilot projects is encouraging, additional research in the field is required to determine the performance of these materials in the stress of daily traffic, changes in climate conditions, and prolonged damage and deterioration. There is a need for long-term data on the durability, maintenance requirements, and lifetime cost of the low-carbon solutions in order to ascertain whether these alternatives are feasible throughout the entire lifespan of the highways^[90].

7.5.2. Development of New, Low-Carbon Materials

There is also a need to conduct further research on the development of new low-carbon materials. As an example, more effective carbon-negative concrete, bio-based asphalt, and other binders could have a significant impact on reducing emissions during the construction stage. Recyclable, resource-efficient, and energy-efficient innovations in materials are also important in regard to the achievement of the near-zero carbon highways goal.

7.5.3. Integrating Smart Technologies

As with highways getting more connected and data-driven, there is a necessity to conduct research on how smart technologies can be combined with sustainable building practices. Near-zero carbon highways will be heavily dependent on developing smart infrastructure that will maximize energy, minimize emissions, and fund electric vehicle infrastructure.

7.6. Overcoming Barriers and Advancing Low-Carbon Highways

It will take a lot of technical, economic, institutional, and social hurdles to have near-zero carbon highways. These obstacles may seem daunting, but they can be overcome. With further research, policy development, collaboration with industries, and involving the people, there is a possibility of establishing the path to highways that would be not only efficient and safe, but also help in the process of reducing climate change all over the world. By tackling these barriers directly and filling the gaps in the research, the low-carbon highways will become the norm and not the exception in the changing environment of sustainable infrastructure^[29].

8. Future Perspectives and Recommendations

With the growing trend in adopting carbon neutrality globally, the future of highway infrastructure will become more reliant on the implementation of low-carbon technologies, new materials, and sustainable operations. Nonetheless, despite the fact that significant progress has been made, the road to almost zero-carbon highways is not entirely covered. In this section, the writer examines the future of highway infrastructure and offers advice on the research, policy, industry practice, and technological application that would speed up the process of conversion to a sustainable and low-carbon transportation system. It also describes how emerging trends, including the emergence of smart infrastructure and digital technologies, are going to shape the future of highways.

8.1. Research and Development in Low-Carbon Materials and Technologies

Research and innovation of low-carbon materials and technologies is one of the most crucial fields of future de-

velopment in highway infrastructure. Although considerable progress has been made in the use of materials such as geopolymer cement, warm-mix asphalt, recycled aggregates, and so on, there is a lot that can be done to make these materials applicable in the construction of highways on a large scale.

8.1.1. Advancing Low-Carbon Construction Materials

The future of low-carbon materials continues to be the role of sustaining alternative materials to the conventional high-carbon materials like Portland cement and asphalt. As an example, carbon-negative concrete and bio-based asphalt have been promising in terms of reducing emissions, although more studies are required on their durability, performance, and cost-effectiveness.

Also, the circular economy model, which implies the reuse and recycling of available materials, must be given attention. The studies of more developed recycling technologies allowing the reclaiming of more materials, including concrete and asphalt, and reusing them in new buildings, will play a major role in mitigating the carbon footprint of roadways. Asphalt pavement can be recycled (recycled asphalt pavement (RAP)) or concrete can be recycled (recycled concrete aggregate (RCA)), and steel slag can also be used in place of virgin resources, but scalability and cost-efficiency are the issues that need to be researched^[91,92].

8.1.2. Innovative Technologies for Sustainable Highways

The introduction of new technologies in the building industry, including 3D printing, modular construction, and automated construction machinery, can considerably decrease the carbon footprint of highway projects. These technologies provide the prospects of accuracy, minimization of waste, and efficiency of resources. As an example, 3D printing can minimize the amount of waste in the form of materials since it can be used to print road structures precisely, whereas modular construction can minimize the number of people and energy required on-site, which positively affects the overall efficiency and minimizes emissions.

Moreover, intelligent highways that incorporate electronic sensors, automated cars, and electric vehicle (EV) networks will transform the manner in which highways are built and run. These technologies not only lessen the emissions of vehicles on the road, but also enhance traffic movement,

hence less fuel and less congestion. The future studies must aim at incorporating smart technologies into sustainable construction and developing highways that are energy-efficient, carbon-neutral, and climate-resistant^[93].

8.2. Policy and Regulatory Recommendations

Technological innovation will not be sufficient to facilitate a successful shift to low-carbon highways, but rather will need robust and coherent action on the policy and regulatory front. Governments have a decisive role in the development of sustainable infrastructure, where the policy frameworks, standards, and incentives are given to focus on the low-carbon highways.

8.2.1. Developing Comprehensive Sustainability Policies

There is a need to make sustainability a concern of governments in their transportation infrastructure policies. This involves the creation of all-encompassing rules that define carbon cut-offs on the highway projects and offer clear-cut directives on the construction materials, maintenance processes, and operation plans for low-carbon. Carbon pricing schemes like carbon taxes or emissions trading schemes can also be used to appeal more to curbing emissions in highway projects. Moreover, material, technology, and construction practices sustainability standards should be standardized in order to be consistent among the projects. The nations that are already on the trail of sustainable infrastructure, e.g., the European Union countries, have already established strong green infrastructure standards that can be replicated and spread to other countries^[94].

8.2.2. Financial Incentives and Funding Mechanisms

Financial incentives and funding mechanisms will be vital in order to hasten the use of low-carbon technologies. The governments can provide incentives in terms of grants, subsidies, or tax credits in order to promote the utilization of green technologies and sustainable materials in highway construction. Such incentives would allow compensating the high upfront costs of low-carbon options and stimulate the investment of the private sector in sustainable infrastructure.

Financing sustainable highway projects can also be achieved through the participation of public-private partnerships (PPP). These alliances are capable of offering the funds

required for research and development, not to mention the execution of innovative solutions. Governments must look at co-investing in green infrastructure projects and establishing a framework of sustainable highways as a rule, and not an exception^[95].

8.3. Industry Practices and Collaboration

The highway construction industry also needs to transform in order to adopt sustainability at all levels of the project life cycle. Co-operation of engineers, designers, contractors, governments, and research institutions is very important in enhancing innovation and making sure that sustainable practices are implemented in the entire process.

8.3.1. Fostering Industry Collaboration

To come up with a sustainable highway infrastructure, the highway sector stakeholders must work together. Research establishments can collaborate with the industry players in coming up with new materials with low carbon and new construction methods. Also, it can be proposed to collaborate with communities living in a certain area to define the problems and the ways to solve them, making sure that low-carbon highways are designed in a manner that will not harm the environment of the local community and will maximize social welfare.

Education and training of workers in the construction business should be done in concert to learn the current low-carbon technologies, sustainable practices, and green certifications. An investment in skill development will mean that the workforce is ready to meet the need to create a sustainable infrastructure, both in construction and operation^[96,97].

8.3.2. Standardizing Green Infrastructure Practices

Standardized practices on green highway construction will offer a road map on how the practices can be extensively implemented. Setting up principles and standards of green construction materials, carbon tracking, and sustainable maintenance will enable the governments and the private companies to compare various projects and make more informed decisions. These standards must be all-encompassing, covering all highway development, including material choice, operation, and maintenance. Development of sustainable road design practices into a standard will also encourage efficiency and cost-effectiveness, as it will be easy

to incorporate low-carbon technologies without the fear of determining the costs or the performance of the new move^[98].

8.4. Technology and Innovation Integration

The digital solutions and the incorporation of smart technologies are closely interconnected with the future of highway infrastructure. These technologies are able to optimize not only the energy consumption, traffic, and car emissions, but also the general resiliency and sustainability of the road systems. The advancement of the next generation of low-carbon highways will require adopting the latest innovations, including smart sensors, Internet of Things (IoT), real-time data analytics, and artificial intelligence (AI).

Smart Roads and Sustainable Transportation

Smart roads will entail the incorporation of real-time data collection and adaptive traffic management systems to streamline traffic flow, minimize congestion levels, and decrease fuel usage. This will cause great cutbacks in the carbon emissions of the operation. In addition, intelligent roads will be of great use in highway maintenance because they will be able to predict wear and tear on the road surface, and therefore be able to perform predictive repairs to eliminate future maintenance problems and cut emissions during maintenance.

Another development is the integration of electric vehicle charging infrastructure into highways. The development of highways in the future ought to accommodate the common use of electric vehicles through the installation of fast-charging stations on highways. This will not only be beneficial for low-carbon mobility but also lead to a greener transportation system, as it will minimize vehicle emissions across the entire structure^[99,100].

8.5. Advancing towards Near-Zero Carbon Highways

The solution to this is in the sustainability of the highway infrastructure in all walks of life, including its design, construction, operation, and maintenance. With the improvement of technology, new materials are created, and the research of sustainable practices is increasing; the dream of near-zero carbon highways is becoming a possibility. Nonetheless, to achieve this vision, it will need to be accom-

plished through concerted effort in the field of research, policy, industry, and society. The highway industry can greatly impact the environment through innovation, cooperation, and effective regulatory measures to help achieve sustainability in the global arena. The benefits of low-carbon highways are twofold: not only will carbon emissions decrease, but this method will also present one of the blueprints according to which transportation infrastructure will become a key component of a sustainable, low-carbon future.

9. Conclusions

The innovation of low-carbon highways is an essential aspect of the larger process of climate change reduction and the transition of infrastructure to a sustainable level. With the constantly increasing need for transportation infrastructure requirements all over the world, there is a need to ensure that we do not just look at the immediate needs of mobility but also the long-term environmental implications of the highway systems. The carbon footprint of highways can be lowered by applying green technologies, low-carbon materials, smart infrastructure, and sustainable operational practices, which can help the world reach a net-zero level of emissions.

We have analyzed the different aspects of low-carbon highway construction in this review, such as new construction materials, such as geopolymer cements and recycled asphalt, as well as digital solutions that streamline traffic flow and minimize emissions. Smart traffic management, electric vehicle infrastructure, and predictive maintenance systems are the strategies that have shown great potential for cutting down emissions in the operation stage. In addition, Lifecycle Assessment (LCA) and carbon accounting give invaluable resources in measuring and tracking the carbon footprint of highways in order to ensure that carbon reduction strategies are applied in an efficient manner and performance is achieved in a continuous manner.

But there are still great obstacles. The barriers to the spread of sustainable practices in the construction and operation of highways and roads remain as technical constraints, high initial costs, and institutional barriers. Moreover, data breaks, territorial diversity, and the necessity to have standardized regulations are also other obstacles that have to be addressed. These obstacles emphasize the necessity to move on with research, policy changes, and cross-sector and

cross-region collaboration.

Nonetheless, the future is bright. We can speed up the transition to near-zero carbon highways by enhancing the innovation of materials science, the development of digital technologies, and the creation of harmonized regulatory systems. Governments, industrial leaders, and research institutions should collaborate to develop favorable policies and incentives with a focus on sustainability in highway development. In the end, a new generation of highways that are low-carbon and environmentally-friendly will not only be more efficient and environmentally friendly, but will also help in the creation of a robust and sustainable transport system that will cater to the needs of the people and the environment.

The trend towards the incorporation of sustainability into the highway infrastructure needs to be the rule, as opposed to the exception. Through persistent work and cooperation, highways with almost zero carbon emissions will be realized and will help prepare the future of a low-carbon and sustainable transport system that will be used by future generations.

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