

Article

Life Cycle Assessment for CO₂ Emissions and Mitigation Pathways During the Expressway Construction Phase: A Case Study in Central China

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Abstract

Reducing carbon emissions from highway construction is vital for mitigating climate change. Based on an expressway project in central China, this study conducted a fine-grained CO₂ emission accounting and analysis. The findings reveal that bridges and culverts rank first in emissions among all subprojects, emerging as a “carbon hotspot” with an exceptionally high emission intensity, followed by subgrade and pavement. Additionally, traffic safety facilities, accounting for 6.40% of total emissions, are also not negligible. Regarding emission sources, material emissions exhibit an extreme dominance at 89.44%, whereas off-road machinery and transport vehicles demonstrate distinct patterns of input-emission asymmetry and single-vehicle-type dominance, respectively. Consequently, this study delineates decarbonization pathways, quantitatively verifies the low-carbon efficacy of four mitigation technologies, and focuses on evaluating the environmental-economic dual feasibility of substituting core equipment with pure electric alternatives. The results demonstrate that the resin-bonded gravel sound barrier achieves an emission reduction rate of 73.26%; furthermore, under a 50% penetration rate, deploying 30-ton class EV dump trucks can cut transportation emissions by 9.98%, maintaining exceptional financial resilience even under a 30% plunge in diesel prices. This study provides a replicable, scientific decision-making basis for the deep decarbonization of the transportation infrastructure sector.



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1. Introduction

The transportation sector accounts for 23.9% of global CO₂ emissions [1]. Highway construction, a highly resource-intensive component, is a primary emission source. Quantifying road infrastructure emissions and exploring mitigation pathways are critical. Early research established macro Life Cycle Assessment (LCA) frameworks evaluating entire

construction lines [2] and large-scale corridors like Egnatia Odos [3]. To enhance precision, researchers incorporated uncertainty analyses for Chinese projects [4], quantified provincial footprints [5], and evaluated expressway networks [6]. Specific case studies have further expanded macro-estimations to urban road corridors [7,8]. Simplified LCA methods quantified municipal footprints in Shenzhen [9], while precise boundary truncation thresholds ensured macro-estimation accuracy [10]. Beyond direct construction, indirect emissions from upstream cement and steel supply chains offer cross-mitigation potential [11]. Scenario analysis predicted life-cycle emission trends under low-carbon models [12]. Furthermore, a difference-in-differences model analyzed Chinese county-level emissions to investigate “carbon lock-in” effects from infrastructure policies [13].

At the project scale, significant emission heterogeneity exists. Bill of Materials-based studies show raw material production dictates project-level emissions [14]. Subprojects like bridges, tunnels, and interchanges are dominant emission contributors [15]. For instance, bridge and tunnel emission intensities on a southwest China highway are 6.8 and 8.1 times higher than on ordinary roads [2]. To facilitate early-stage quantification, predictive models combining Modified Northern Goshawk Optimization with BP neural networks [16] and scenario-based Long Short-Term Memory algorithms [17] were developed. For bridges, materials remain the primary emission source [18]. Machine learning, particularly Gradient Boosting Regression Trees, outperforms traditional methods for predicting bridge emissions [19], while Autoencoders achieve accurate tracking in reconstruction scenarios [20]. To optimize designs, Building Information Modeling with metaheuristic algorithms minimized prefabricated T-beam embodied carbon [21], and studies compared precast versus cast-in-place box girders [22]. Network-level management utilizes NSGA-III algorithms balancing maintenance, reliability, and detour emissions [23], while LCA studies confirm the decarbonization benefits of epoxy asphalt [24]. Tunnel engineering presents complex profiles; AutoML frameworks predict embodied carbon for drill-and-blast and shield tunnels [25]. Integrated 3D models identify initial support and secondary linings as hotspots [26]. Modified process analyses with CNN-LSTM networks provide full-process precision for shield tunnels [27], and systematic quantification methods exist for immersed tunnels [28].

The micro-mechanisms of material production and machinery operation underpin road carbon accounting. Raw material extraction and processing remain the largest environmental burdens [29]. Studies tracked energy and material flows throughout supply chains to evaluate breakthrough technologies [30]. In asphalt production, aggregate and bitumen heating generate the highest energy consumption [31]. Consequently, LCA models for Reclaimed Asphalt Pavement (RAP) analyzed uncertainties and proposed reduction measures [32]. These uncertainties are mitigated by intelligent variability controls maximizing RAP inclusion [33]. Regarding machinery, system boundary selections cause massive estimation discrepancies [34]. Reviews systematized emission sources [35], supported by a dedicated, Excel-based pavement LCA model [36]. Hybrid LCA-LCC models detail milling and repaving equipment fuel emissions [37], quantitative decision models pinpoint operational hotspots [38], and the ACEMO-TOPSIS algorithm optimizes machinery scheduling across duration, cost, and carbon footprints [39].

Driven by robust accounting, various green technologies are implemented. Integrating LCA with Life-Cycle Cost Analysis supports sustainable pavement selection [40] and clarifies emission intensities across Chinese highways to evaluate low-carbon potentials [41]. Warm Mix Asphalt (WMA) and RAP are prominent strategies [42], with WMA and natural gas drastically reducing heating energy [43]. Comparative assessments prove Cold In-place Recycling yields exceptional emission reductions [44]. Emission differences between asphalt and Portland cement mixtures were thoroughly assessed [45]. Integrating

whole-structure and in situ recycling for old cement pavements aids renovation technology upgrades [46]. Maintenance studies show micro-surfacing and in-place recycling outperform traditional methods [47]. Material optimization reduces virgin dependency via high-RAP mastics [48], cement-stabilized phosphogypsum [49], and alkali-activated bottom ash [50]. Waste-modified asphalt incorporating crop straw and tire rubber prevents incineration pollution while reducing emissions [51]. Broader reviews assessed ten innovative cross-sector technologies, evaluating greenhouse gas mitigation potentials [52]. Achieving systemic reductions requires active stakeholder synergy, demonstrated by evolutionary game models [53]. Furthermore, green procurement strategies like those in Flanders evaluate open tenders by incorporating construction-induced CO₂ emissions and traffic disruptions [54].

Despite the extensive advancements in macro-level accounting and the evaluation of traditional low-carbon materials technologies, critical research gaps remain in systematic, project-level evaluations. First, existing research on carbon emission accounting for highway construction is often limited to main subprojects such as subgrades, pavements, bridges, and tunnels, and only focuses on a few key materials and mechanical equipment; thus, there is still room for improvement in the comprehensiveness of accounting boundaries and data precision. Furthermore, achieving deep decarbonization in highway construction relies not only on the precise quantitative verification of existing traditional technologies but also on the assessment of new low-carbon technologies to push the boundaries of emission reduction. Secondly, although the decarbonization of construction machinery has become an industry consensus, feasibility studies targeting electrified equipment and vehicles in construction scenarios remain scarce. To bridge these gaps, this study conducts a comprehensive carbon emission assessment of an actual expressway project based on detailed Bill of Quantities and Construction Cost Estimate Documents. Specifically, this paper highlights three distinct contributions: (1) by incorporating a broader range of materials, equipment, and transport vehicles into the accounting scope across six key subprojects, it achieves the precise identification of high-emission hotspots, notably revealing traffic safety facilities as a non-negligible emission source; (2) it provides quantitative verification of four specific emission reduction technologies adopted in the project, demonstrating, in particular, the impressive mitigation performance of the resin-bonded gravel sound barrier; and (3) it conducts an integrated environmental-economic assessment of equipment electrification to evaluate potential machinery alternatives. Through these contributions, this study aims to refine the carbon accounting system for highway infrastructure construction and propose feasible, highly efficient mitigation pathways with practical significance.

2. Materials and Methods

2.1. Scope and System Boundary

In accordance with ISO 14040 and ISO 14044 standards [55,56], this study adopts the LCA approach. While a full highway life cycle includes operation, maintenance, and end-of-life stages, this assessment specifically focuses on the construction phase. The application of the LCA methodology here ensures that not only direct on-site emissions from construction activities are accounted for, but also the significant upstream embodied emissions associated with raw material extraction, manufacturing, and energy production. Within this defined system boundary, expressway construction projects comprise various engineering subprojects, including subgrade, pavement, bridges and culverts, traffic safety facilities, landscaping, and electromechanical systems. The CO₂ emissions of the project are quantified by aggregating the emissions across these subprojects. Ultimately, this study

encompasses three core emission sources: material production, off-road machinery, and transport vehicles. Their specific definitions are as follows:

- **Material production emissions:** These encompass the full-process emissions ranging from the extraction of natural resources and intermediate processing to the final manufacturing of construction materials.
- **Off-road machinery and transport vehicles emissions:** These encompass the direct emissions from terminal fuel combustion, as well as the indirect emissions from upstream fuel and electricity production processes.

System boundary exclusion clarification: External transportation was excluded from the accounting scope of this study due to the unavailability of data from the construction contractors, coupled with the fact that transportation distances for materials from factories to the construction site vary significantly across highway projects depending on geography, topography, geology, and the distribution of local suppliers. For example, external transportation in the three projects assessed in [2] accounted for 2.4%, 1.0%, and 1.1% of total emissions, respectively, while it accounted for only 0.7% in the case study presented in [10]. Additionally, another case project reported external transportation emissions accounting for 1.31%, whereas its comparative project reached 13.1% [7]. Similarly, a proportion of 10.88% was reported [57]. It should be noted that the external transportation in the latter two studies [7,57] included not only material transport but also the transportation of heavy machinery to the site. The differences among various projects are substantial; even within the same study [2], the highest external transportation proportion is 2.4 times the lowest. This high degree of “project specificity” significantly weakens the comparability of carbon accounting results among different projects. Furthermore, the external transportation of materials is often managed by factories or suppliers, falling outside the direct control scope of the construction contractors. In this study, “transportation” within the system boundary refers exclusively to the internal dispatch of materials and the transfer of waste within the construction site. Crucially, the literature indicates that the emission share of external transportation is relatively low in most cases. It is only in highly specific project scenarios, and particularly when additionally accounting for the transportation of heavy machinery to the site, that this proportion exceeds 10%. Therefore, this omission only marginally dilutes the relative emission percentages of other sources and does not fundamentally alter the primary conclusions regarding the identified carbon hotspots.

It should be noted that the quantitative analysis in this study focuses on CO₂ and does not include other greenhouse gases (e.g., methane or nitrous oxide). For simplicity and in alignment with common engineering practice, the terms “carbon emissions” and “CO₂ emissions” are used interchangeably throughout this manuscript.

2.2. Calculation Methods

The carbon emissions from material production can be expressed as:

$$E_i = q_i \times \alpha_i \times ef_i \quad (1)$$

in which i —material type i , q_i —amount of material i , α_i —unit conversion factor for material type i (dependent on the measurement unit of the material consumption and the unit of its carbon emission factor), ef_i —emission factor for the production of material i .

The carbon emissions from off-road machinery can be expressed as:

$$E_j = n_j \times (q_{j,l} \times ef_l + q_{j,elec} \times ef_{elec}) \quad (2)$$

in which, j —machine type j , n_j —numbers of machine-shifts of machine j , l —fuel type l , $q_{j,l}$ —amount of fuel l consumed per machine-shift by machine j , $q_{j,elec}$ —amount of

electricity consumed per machine-shift by machine j , ef_{elec} —emission factor of electricity generation, ef_l —emission factor of fuel l , which can be expressed as:

$$ef_l = ef_{prod,l} + ef_{comb,l} \quad (3)$$

in which, $ef_{prod,l}$ —emission factor for the production of fuel l , $ef_{comb,l}$ —emission factor for the combustion of fuel l .

The carbon emissions from transport vehicles can be expressed as:

$$E_k = n_k \times (q_{k,l} \times ef_l + q_{k,elec} \times ef_{elec}) \quad (4)$$

in which, k —vehicle type k , n_k —numbers of machine-shifts of vehicle k , $q_{k,l}$ —amount of fuel l consumed per machine-shift by vehicle k , $q_{k,elec}$ —amount of electricity consumed per machine-shift by vehicle k .

The carbon emissions of the subproject can be expressed as:

$$E_m = E_{mat,m} + E_{mac,m} + E_{veh,m} \quad (5)$$

in which, m —subproject m , $E_{mat,m}$ —material production emissions of subproject m , $E_{mac,m}$ —off-road machinery emissions of subproject m , $E_{veh,m}$ —transport vehicle emissions of subproject m .

The total carbon emissions of the project can be expressed as:

$$E_{tot} = \sum_m E_m \quad (6)$$

2.3. Case Project Introduction and Data Collection

The expressway in this case study is located in the plains and rolling terrain of central China. Designed as a four-lane divided expressway, the project encompasses subgrade, pavement, bridges and culverts, traffic safety facilities, landscaping, and Electromechanical systems. The length of each subproject is summarized in Table 1.

Table 1. Length of each subproject.

	Subgrade	Pavement	Bridges and Culverts	Traffic Safety Facilities	Landscaping	Electromechanical Systems
Length (km)	124.91	124.91	23.93	148.84	148.84	148.84

Material consumption and machine-shift data for off-road machinery and transport vehicles were sourced from the detailed Bill of Quantities and Construction Cost Estimate Documents. Per-shift fuel and electricity consumption for off-road machinery and transport vehicles is directly sourced from the latest Highway Engineering Machinery Shift Cost Quota (the Quota), published by the Ministry of Transport of China, which also serves as the standard applied during the case project's construction and represents the national average productivity level. Furthermore, four emission-reduction technologies were adopted as variations during construction. Their associated material and machine-shift data relied on actual engineering records supplied by the contractor, evaluated against a control group of four corresponding conventional construction technologies.

To ensure accurate and reliable emission accounting, localized Chinese emission factors are prioritized for material production, fuel and electricity generation, and fuel combustion. These data are primarily sourced from two continuously updated databases: the China Products Carbon Footprint Factors Database (CPCD, published by the Chinese

Academy of Environmental Planning under the Ministry of Ecology and Environment) and the Chinese Life Cycle Database (CLCD, by Sichuan University and IKE). Furthermore, the 2023 Electricity CO₂ Emission Factor (issued by the Ministry of Ecology and Environment and the National Bureau of Statistics) is applied, representing the latest official data aligning directly with the project's construction period. The CO₂ emission factors for the primary materials and energy are presented in Table 2.

Table 2. CO₂ emission factors for primary materials and energy.

Materials/Energy	CO ₂ Emission Factor	Unit
Cement	0.88	kg/kg
Steel	4.08	kg/kg
Quicklime	0.80	kg/kg
Crushed stone	2.18	kg/t
Asphalt	0.24	kg/kg
Diesel	3.80	kg/kg
Gasoline	3.67	kg/kg
Electricity	0.5306	kg/kWh

3. Results

3.1. Breakdown of CO₂ Emissions

The total carbon emissions during the construction of the investigated expressway project amount to 3,017,173.70 tCO₂. As shown in Figure 1a, bridges and culverts, along with subgrade engineering, dominate the subprojects, yielding 1,208,538.83 tCO₂ (40.06%) and 1,177,664.45 tCO₂ (39.03%), respectively. These are followed by pavement (12.85%) and traffic safety facilities (6.51%), with landscaping (0.99%) and electromechanical systems (0.56%) contributing marginally. Furthermore, as shown in Figure 1b, by emission source, material production accounts for an overwhelming 89.36% (2,696,060.75 tCO₂). Non-road machinery and transport vehicles contribute 6.50% and 4.15% to the total emissions, respectively.

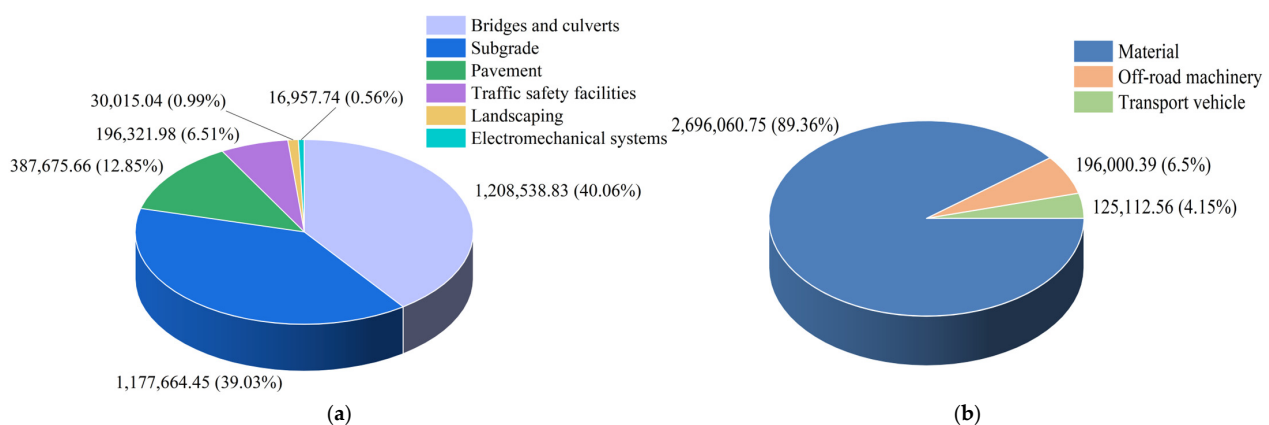


Figure 1. Breakdown of CO₂ emissions: (a) by subproject; (b) by emission source. (unit: tCO₂).

3.2. Carbon Reduction of the Applied Technologies

During construction, the project adopted four emission-reduction technology variations. For a comparative analysis, the contractor provided actual engineering data for these technologies alongside corresponding data for conventional methods to establish a baseline. It should be noted that the data for the “conventional” baseline technologies evaluated in this study are derived from the contractor’s historical construction records, carefully integrated with the specific context of the current project. These selected technolo-

gies represent the typical, traditional, and most widely adopted construction practices in the field, effectively reflecting the industry average level. This selection ensures that the baseline provides a reliable and representative benchmark for evaluating the subsequent mitigation pathways. As shown in Table 3, all four technologies achieved varying degrees of carbon reduction.

Table 3. Carbon reduction effects of the four applied technologies. (unit: tCO₂).

Construction Scenarios	Δ Off-Road Machinery Emissions	Δ Transport Vehicle Emissions	Δ Material Emissions	Δ Total	Emission Reduction Rate	Affiliated Subproject
Steel Slag Asphalt Mixture Natural Aggregate Asphalt Mixture (Baseline)	30.38	0.12	−30.99	−0.48	0.06%	Pavement
Precast Reinforced Concrete Bridge Cast in situ Reinforced Concrete Bridge (Baseline)	−2913.16	−27.28	1952.57	−987.87	0.73%	Bridges and culverts
Resin-bonded Gravel Sound Barrier Metallic Noise Barriers (Baseline)	−6.67	-	−3440.99	−3447.67	73.26%	Traffic safety facilities
Humus Soil Slope Protection Topsoil Slope Protection (Baseline)	-	-	−356.28	−356.28	91.47%	Landscaping

In terms of absolute reduction, the resin-bonded gravel sound barrier performed best, reducing emissions by 3447.67 tCO₂, followed by prefabricated reinforced concrete bridges (987.87 tCO₂). Notably, the latter exhibited a “carbon emission transfer” effect: although prefabricated components increased material production emissions (requiring additional steel elements and utilizing higher-grade concrete and high-strength grout) by 1952.57 tCO₂, they significantly optimized on-site operations, reducing off-road machinery emissions by 2913.16 tCO₂ and yielding an overall net reduction of 0.73%. This demonstrates that the substantial on-site machinery emissions of cast-in-place construction are transferred upstream to the material production phase in prefabrication. Consequently, it underscores that emission reduction strategies must extend beyond on-site operations to encompass upstream emissions, preventing the oversight of such carbon transfer phenomena when evaluating mitigation technologies or pathways.

Furthermore, minimizing on-site machinery schedules through prefabrication offers significant operational advantages. Specifically, relocating the bulk of heavy equipment operations to off-site factories dramatically alleviates local traffic disruptions and lowers safety risks for construction personnel by reducing equipment congestion in active work zones.

Regarding reduction efficiency, the protective utilization of humus soil and the resin-bonded gravel sound barrier achieved exceptionally high rates of 91.47% and 73.26%, respectively. Their benefits stemmed almost entirely from material substitution, cutting 356.28 tCO₂ and 3440.99 tCO₂, respectively. Conversely, while the steel slag asphalt mixture reduced material production emissions, its inherently higher apparent density significantly increased the total mass of the mixture. This added weight demanded greater energy at the mixing plant and imposed higher load burdens on transport vehicles, offsetting most upstream gains and resulting in a marginal net reduction of 0.06%.

3.3. Carbon Emission Intensity for Each Subproject

After accounting for the four technology variations, the final carbon emissions decrease to 3,012,381.40 tCO₂, corresponding to a carbon emission intensity of 5059.76 tCO₂/lane-km. Given that the reduction amount is marginal relative to the emissions of individual subprojects and the three emission sources, their carbon emission amounts and proportional distribution remain largely unchanged compared to Figure 1a.

Furthermore, the analysis of emissions per lane-km, illustrated in Figure 2, reveals that bridges and culverts are highly carbon-intensive. They not only account for the largest absolute emissions but also reach a remarkable intensity of 12,613.87 tCO₂/lane-km. In contrast, the emission intensities for subgrade, pavement, and traffic safety facilities drop significantly to 2357.06, 775.92, and 323.96 tCO₂/lane-km, respectively. The remaining subprojects all fall below 50 tCO₂/lane-km, with electromechanical systems being the lowest at 28.48 tCO₂/lane-km.

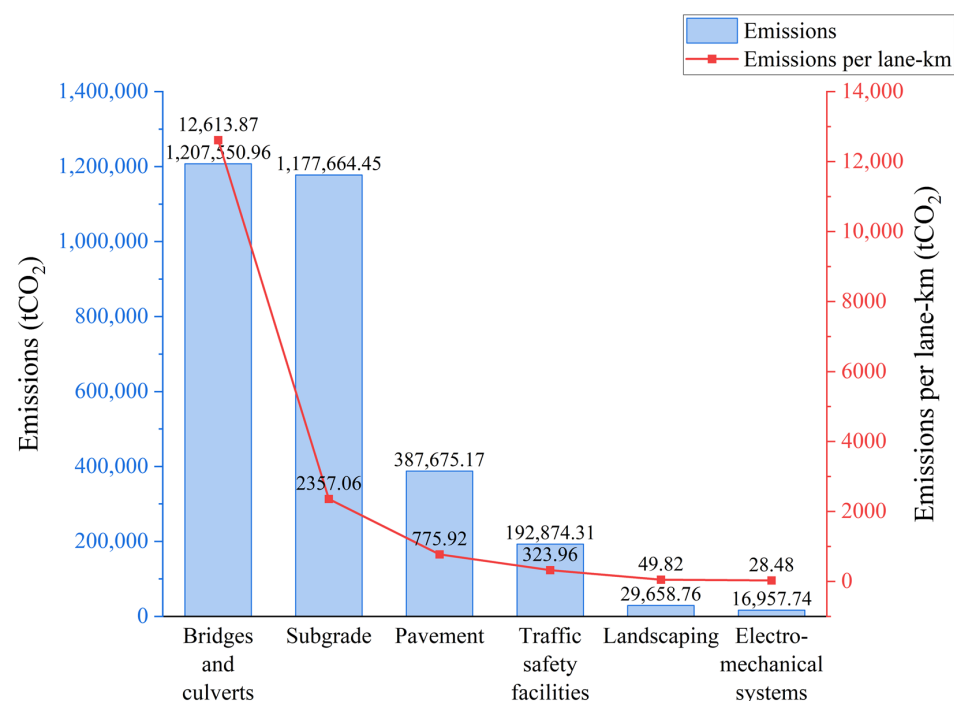


Figure 2. Carbon emissions and emission intensity for each subproject.

3.4. Emission Source Composition Across Subprojects

An analysis of the emission source composition across subprojects, illustrated in Figure 3, reveals that material production overwhelmingly dominates in all six categories. In traffic safety facilities, electromechanical systems, bridges and culverts, and landscaping, material emissions exceed 94% (reaching 98.76%, 97.51%, 96.87%, and 94.31%, respectively). Consequently, the contributions of off-road machinery and transport vehicles in these subprojects are marginal—with only landscaping transport vehicles exceeding 3% (4.65%)—indicating that their carbon emissions are almost entirely dictated by material choices.

Conversely, pavement and subgrade engineering exhibit distinct emission structures. In pavement engineering, the intensive utilization of heavy equipment for paving and compaction drives the off-road machinery share to a peak of 20.33% among all subprojects, while the material share drops to a minimum of 77.43%. For subgrade engineering, materials, off-road machinery, and transport vehicles account for 84.00%, 9.04%, and 6.96%, respectively; notably, the transport vehicle share reaches its maximum among all subprojects due to extensive earthwork distribution.

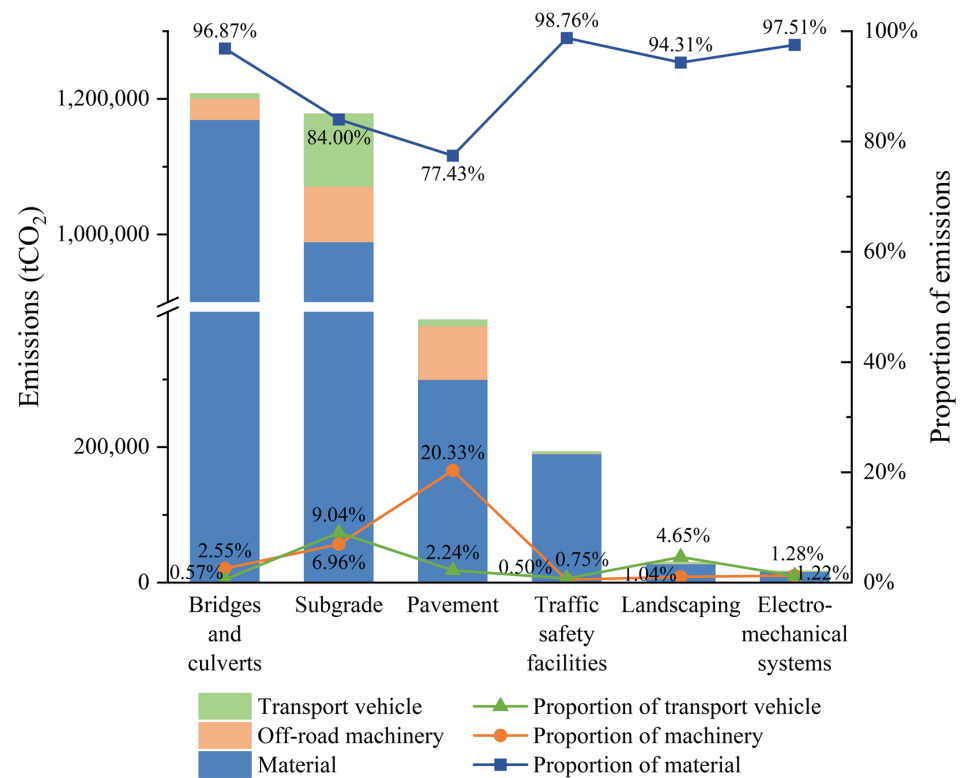


Figure 3. Breakdown of carbon emissions for each subproject by source.

3.5. Carbon Emissions of Core Materials

Material production overwhelmingly dominates, accounting for 2,694,185.06 tCO₂ (89.44%). Given the vast diversity of construction materials, this study further isolates the top 11 core materials with the highest carbon contributions, collectively accounting for over 96% of the total material emissions. Their absolute emissions and cumulative contribution rates are illustrated in Figure 4.

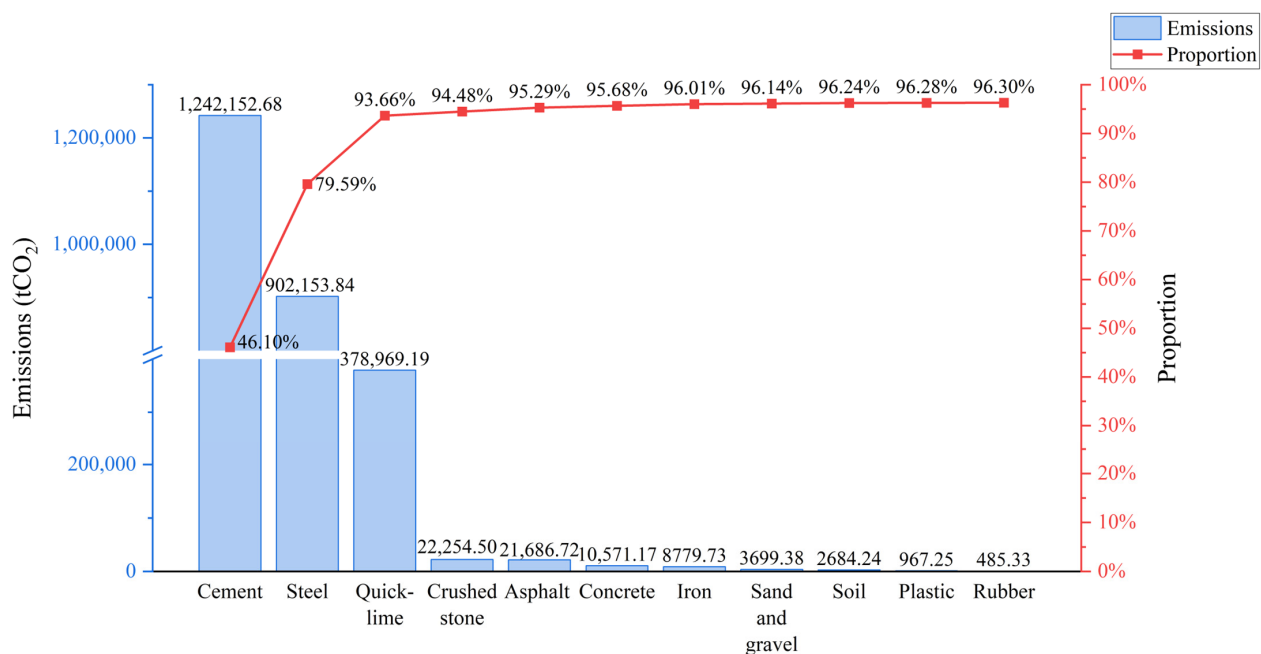


Figure 4. Carbon emissions and cumulative contribution rates of the core materials.

The data results indicate that the carbon emissions of construction materials exhibit an exceptionally high degree of concentration. Specifically, cement acts as the primary core carbon emission source in the project, with its emissions reaching as high as 1,242,152.68 tCO₂, accounting for 46.10% of the total material emissions. Steel follows closely behind with emissions of 902,153.84 tCO₂; the emissions from these two materials alone collectively account for nearly 80%. Quicklime, extensively utilized for subgrade soil stabilization across massive earthworks, serving as the third-largest emitting material, generates 378,969.19 tCO₂, further driving the cumulative carbon contribution rate of the top three core materials up to 93.66%. In contrast, the carbon emissions of the remaining eight materials listed in the figure exhibit a sharp decline. Among them, the emissions of crushed stone and asphalt, ranking fourth and fifth, plummet to 22,254.50 tCO₂ and 21,686.72 tCO₂, respectively; meanwhile, the incremental contributions to the total emissions from materials such as concrete, iron, sand and gravel, soil, plastic, and rubber are extremely marginal.

3.6. Carbon Emissions and Machine-Shift Consumption of Off-Road Machinery

An analysis correlating the carbon emissions of off-road machinery with their machine-shift consumption (illustrated in Figure 5a–f) reveals distinct quantitative distribution patterns across the subprojects.

First, pavement and bridge/culvert engineering exhibit a significant disparity between shift proportions and emission contributions. In pavement engineering, mixing equipment accounts for only 5.87% of the shifts but generates 81.85% (64,507.17 tCO₂) of the emissions. Conversely, road rollers and breakers represent 31.29% and 10.29% of the shifts, respectively, yet their emission proportions are merely 7.24% (5707.24 tCO₂) and 0.34% (271.50 tCO₂). Similarly, drilling rigs and rebar processing machines in bridges and culverts consume a combined 14.65% of shifts while accounting for 45.22% of emissions; in contrast, welding machines and winches occupy 28.12% and 26.91% of the shifts, respectively, but produce only 13.50% (4164.55 tCO₂) and 6.96% (2147.02 tCO₂) of the emissions.

Second, subgrade and traffic safety facilities demonstrate a high positive correlation between machinery emissions and shift scales. In subgrade engineering, road rollers, excavators, and graders record the highest shift inputs at 26.86%, 22.26%, and 20.33%, respectively, and their corresponding carbon emissions collectively account for 76.12% (26,484.56 tCO₂, 19,531.44 tCO₂, and 16,377.18 tCO₂, respectively). Traffic safety facilities follow the same trend, with welding and road marking machines entirely dominating both machine-shift consumption and carbon emissions (both exceeding 97%).

Furthermore, in landscaping, the shift input of cranes (48.17%) is roughly equivalent to their emission proportion (50.29%) as the core emission source; however, excavators and bulldozers contribute nearly 30% of emissions with a combined shift share of less than 10%. In electromechanical systems, maintenance trucks and air compressors contribute 24.87% and 15.80% of emissions from mere shift proportions of 5.29% and 1.80%, respectively.

3.7. Carbon Emissions and Machine-Shift Consumption of Transport Vehicles

An analysis correlating the carbon emissions of transport vehicles with their machine-shift consumption (illustrated in Figure 6a–f) indicates an overall strong positive correlation, although specific vehicle emission shares vary depending on the engineering characteristics of each subproject.

First, dump trucks overwhelmingly dominate the transport vehicle sector in both subgrade and pavement engineering. In subgrade engineering, dump trucks account for 99.54% of the shift inputs and generate 99.70% of the carbon emissions (106,144.24 tCO₂); in pavement engineering, they contribute 94.85% of the carbon emissions (8236.23 tCO₂).

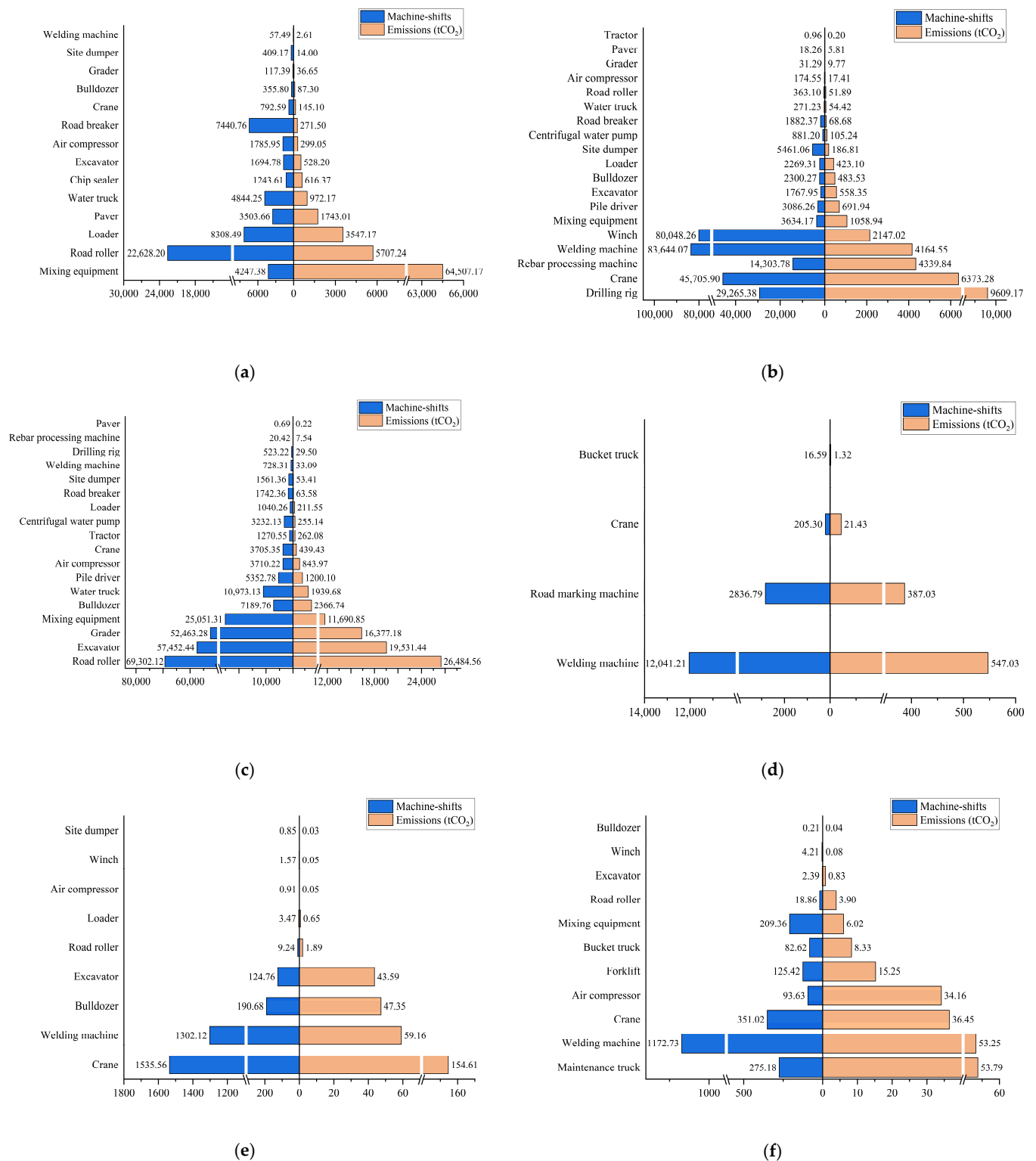


Figure 5. Distribution of carbon emissions and machine-shift consumption for off-road machinery: (a) Pavement; (b) Bridges and culverts; (c) Subgrade; (d) Traffic safety facilities; (e) Landscaping; (f) Electromechanical systems. Note: “Machine-shift” is the unit of operational consumption, defined by the Quota as 8 h of standard operational work per shift for the listed off-road machinery.

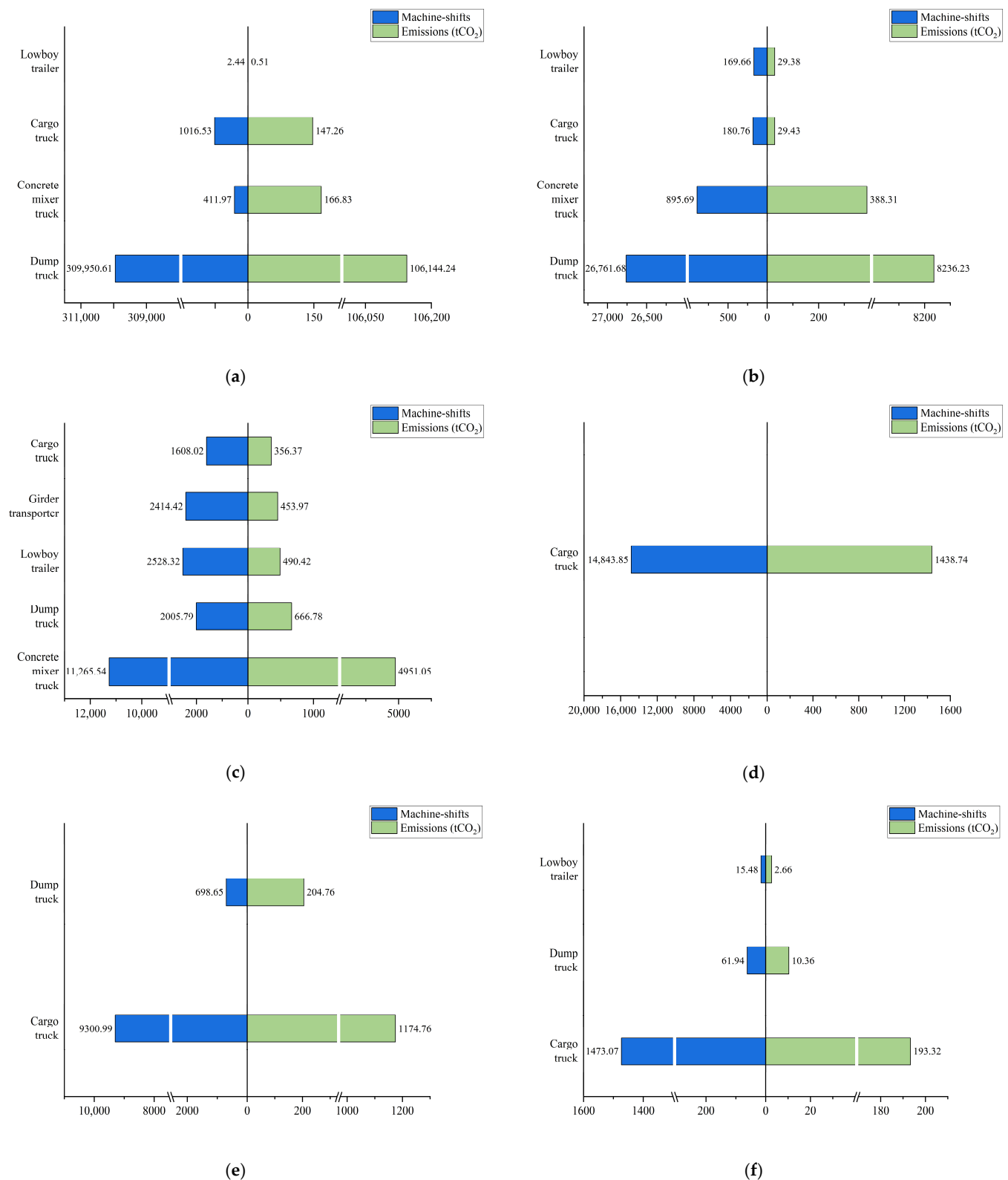


Figure 6. Distribution of carbon emissions and machine-shift consumption for transport vehicles: (a) Subgrade; (b) Pavement; (c) Bridges and culverts; (d) Traffic safety facilities; (e) Landscaping; (f) Electromechanical systems. Note: “Machine-shift” is the unit of operational consumption, defined by the Quota as 8 h of standard operational work per shift for the listed transport vehicles.

Second, transport vehicle emissions in bridge and culvert engineering exhibit a diversified composition, with concrete mixer trucks making the largest contribution at 71.56% of the emissions (4951.05 tCO₂). The remaining emissions stem from dump trucks (9.64%, 666.78 tCO₂), lowboy trailers (7.09%, 490.42 tCO₂), girder transporters (6.56%, 453.97 tCO₂), and cargo trucks (5.15%, 356.37 tCO₂), respectively.

Furthermore, traffic safety facilities, landscaping, and electromechanical systems involve fewer transport vehicle types, all of which are dominated by cargo trucks. Traffic safety facilities exclusively utilize cargo trucks, generating 1438.74 tCO₂ of carbon emissions. In landscaping and electromechanical systems, cargo trucks contribute 85.16% and 93.69% of the carbon emissions, respectively.

4. Discussion

4.1. Comparison and Validation of Carbon Emission Intensity

The quantification of carbon emission intensity is central to evaluating the environmental impact of highway infrastructure. In interpreting the results of this study, a comprehensive comparison with existing literature validates the reliability of our Life Cycle Assessment (LCA) approach. However, to ensure these comparisons are scientifically meaningful, it is imperative to carefully contextualize distinct system boundaries and project-specific structural characteristics.

At the macro-level, we compared our overall project emissions with the findings in Reference [2], which reports total carbon emission densities for three 4-lane highway projects. That study observed 7604 tCO₂/km (1901 tCO₂/lane-km) for Project 1, which primarily consists of small-span bridges, and substantially higher values for Projects 2 and 3, which feature higher proportions of medium- and large-span bridges: 29,677 tCO₂/km (7419.25 tCO₂/lane-km) for Project 2, and 26,524 tCO₂/km (6631 tCO₂/lane-km) for Project 3. Our overall project intensity is 5059.76 tCO₂/lane-km. Because the structural characteristics of our case project are similar to those of Projects 2 and 3 in Reference [2], our total emission intensity falls within a reasonable and expected range.

At the subproject level, we specifically evaluated our pavement emissions (775.92 tCO₂/lane-km) against estimates from References [4,57]. Reference [4] categorizes real-world projects and reports an average of 358.6 tCO₂/lane-km for “high-grade asphalt roads.” Although our estimated magnitude is higher than this value, the discrepancy is justifiable. The “high-grade” classification in Reference [4] broadly aggregates various road types—including lower-tier intercity and interurban roads. The higher intensity observed in our study accurately reflects the substantially thicker asphalt and base layers strictly required for standard expressway construction.

To further contextualize the pavement-specific data, we aligned our system boundaries with a New Jersey case study [57]. To ensure a fair comparison, we focused strictly on CO₂ emissions from materials and construction equipment. This yielded a total of 24,475 tCO₂, establishing an adjusted reference intensity of approximately 950.5 tCO₂/lane-km. Our calculated pavement intensity (775.92 tCO₂/lane-km) is slightly lower but highly consistent with this benchmark. This variance is logically sound, as the total emissions in the reference case were aggregated at the project level; although primarily dominated by pavement construction, their data also incorporated grading, drainage, and sign structures. Therefore, our result accurately reflects the expected magnitude for pavement-specific emissions.

Ultimately, these multi-level comparisons demonstrate that whether evaluated as a full-scale structure or isolated by its specific pavement layers, our data are consistent with established literature. This alignment strongly corroborates the robustness and rationality of our LCA accounting model and intensity estimations.

4.2. Heterogeneity and Structural Mechanisms of Highway Carbon Emissions

The actual total carbon emissions of the highway project reached 3,012,381.40 tCO₂, exhibiting pronounced heterogeneous distribution characteristics across both engineering subprojects and emission sources.

At the macro level, emission intensity varies dramatically across subproject types. Driven by the structural demands of crossing complex terrains and bearing massive loads, bridges and culverts account for only 16.08% of the total mileage but contribute 40.09% of the total emissions, revealing a pronounced peak in emission intensity (12,613.87 tCO₂/lane-km). In contrast, although subgrade engineering generates comparable absolute emissions, the carbon footprint of its massive earthwork operations is “spatially diluted” along the extensive highway axis, reducing its intensity significantly to 2357.06 tCO₂/lane-km. Pavement engineering and traffic safety facilities follow closely in both total emissions and intensity, while landscaping and electromechanical systems—characterized by minimal volumes and lightweight assembly operations—contribute negligibly.

At the micro structural level, this study confirms that highway construction is fundamentally an “embodied-carbon-dominated” process. Material production constitutes the absolute core at 89.44%, whereas off-road machinery and transport vehicles collectively account for merely 10.56%. Based on this mechanism, the engineering subprojects can be accurately classified into two typologies. The first is “material-dominated” (encompassing bridges and culverts, traffic safety facilities, electromechanical systems, and landscaping), where material emissions soar to 94–99%. The second is “on-site construction-intensive” (encompassing pavement and subgrade engineering), where equipment energy consumption significantly surges due to specific operational modes. Specifically, driven by energy-intensive mixing and continuous paving/compaction operations, the off-road machinery share in pavement engineering reaches 20.33%; similarly, extensive earthwork distribution demands in subgrade engineering elevate the transport vehicle share to 9.04%.

4.3. Asymmetric Effects and High Concentration of Emission Sources

First, the material sector exhibits high concentration. Cement, steel, and quicklime cumulatively contribute 93.66% of the total material emissions, constituting the absolute core. This is primarily attributed to their massive consumption base and energy-intensive upstream manufacturing processes; conversely, the environmental impacts of bulk materials like crushed stone and soil are heavily diluted, as they rely solely on simple physical processing. This structural disparity dictates that mitigation strategies must comprehensively target high-carbon materials and advance low-carbon substitution. For instance, the resin-bonded gravel sound barrier utilized in this project successfully replaced traditional metal materials, achieving an emission reduction rate of 73.26%, thereby validating the immense promotional value of low-carbon substitution strategies. Furthermore, quicklime constituted the project’s third-largest material emission source (378,969.19 tCO₂). Replacing this carbon-intensive material with industrial solid wastes and low-carbon binders—such as carbide slag and GGBS-based stabilizers—can provide comparable performance. Integrating these waste-derived alternatives will systematically address a major carbon hotspot while further promoting circular economy principles in highway construction.

However, while the on-site mitigation technologies and substitution strategies evaluated in this study successfully demonstrate emission reductions during the construction phase, it is essential to acknowledge that approximately 90% of the project’s total carbon footprint still originates from embodied material emissions (primarily cement, steel, and quicklime). Therefore, deep decarbonization of highway infrastructure ultimately depends on upstream mitigation pathways within these carbon-intensive industries. The residual embodied emissions can be substantially abated at the production source through the

widespread deployment of Carbon Capture and Storage (CCS) technologies applied to cement plants, steelworks, and the power generation facilities supplying the construction chain. Recent modeling frameworks have successfully validated the technical feasibility of transforming major industrial emitters into net-zero processes through CCS implementation [58]. Furthermore, utilizing depleted geological formations provides robust quantitative evidence for CCS viability, supporting large-scale industrial decarbonization strategies [58]. Integrating these upstream industrial CCS frameworks with on-site construction optimization will provide a comprehensive and policy-relevant pathway toward truly climate-neutral infrastructure.

Second, there is a stark “asymmetry” between the carbon emissions and shift scales of off-road machinery. Mixing equipment exhibits an extreme “low-shift, high-emission” profile, generating 40.01% of the project-wide off-road machinery emissions from merely 5.09% of total operating shifts, whereas winches, road breakers, and welding machines display typical “high-shift, low-emission” characteristics—a divergence that remains highly consistent across all subprojects. The root cause lies in the substantial discrepancy between the equipment’s inherent energy intensity and actual load factor. High-carbon-intensive equipment often involves intense thermal conversion or full-load kinetic output, while low-emission equipment features lower power ratings and highly intermittent operations. This indicates that traditional “one-size-fits-all” shift-reduction strategies are limited in efficacy; future machinery mitigation must implement “precision targeting,” concentrating resources on the technological upgrading and electrification of high-carbon-intensive equipment.

Finally, unlike the asymmetry observed in off-road machinery, transport vehicle emissions exhibit a high degree of concentration and positive correlation. Both the overall project and its individual subprojects are dominated by single vehicle types: dump trucks dominate subgrade engineering (99.70%) and account for 92.15% of the total project transport emissions, with subgrade engineering itself contributing 85.11% of the overall transport emissions. Furthermore, concrete mixer trucks dominate bridge and culvert transport, while cargo trucks perfectly align with the lightweight, discrete logistical demands of traffic safety, landscaping, and electromechanical systems (each exceeding 85% of emissions). Given this high concentration of transport emissions and the fact that construction logistics predominantly rely on fixed routes, this provides an optimal scenario for the electrification of heavy equipment. Prioritizing the deployment of pure electric transport fleets constitutes the most direct and efficient mitigation countermeasure.

4.4. Environmental-Economic Dual Assessment of Electrification Strategies

4.4.1. Carbon Reduction Assessment of Equipment Electrification

Based on the emission accounting results, dump trucks, mixing equipment, road rollers, and excavators rank as the top four sources of combined machinery and transport emissions, accounting for 36.22%, 24.28%, 10.14%, and 6.49%, respectively. Given that mixing equipment is constrained by extreme thermal energy requirements, and pure electric rollers and excavators are still in their nascent commercial stages, this study selects the 30 t-class diesel dump truck—which is the most technologically mature and possesses the largest emission base (constituting 96.10% of total dump truck emissions)—as the baseline for the electrification substitution analysis.

While the electrification of the dump truck presents significant emission reduction potential, practical operational factors such as charging feasibility, infrastructure costs, battery degradation, and payload capacities must be considered. According to the Quota, the working time per shift is calculated at 8 h, leaving ample off-shift time to fully recharge the vehicles without disrupting the daily construction schedule. Economically, a rough cost-benefit analysis demonstrates that charging infrastructure has a minimal impact on

overall feasibility. Furthermore, operational risks are strategically mitigated in our model. The introduction of a larger 600 kWh battery variant provides a necessary capacity buffer to maintain operational range and handle extreme working conditions even as the battery naturally degrades, with standard manufacturer warranties further offsetting part of the financial risks. Finally, by replacing standard 30 t-class diesel dump trucks with larger 37.3 t-class EV dump trucks, the capacity upgrade effectively compensates for any potential reduction in payload, thereby mitigating operational efficiency losses.

Benchmarking against a mature 37.3 t-class EV dump truck in the market, and integrating the per-shift energy consumption of diesel dump trucks from the Quota alongside the per 100 km energy consumption of both diesel and EV dump trucks, it is determined that electric substitution achieves a single-shift emission reduction of 77 kgCO₂ (a reduction rate of 22.53%). Under a conservative scenario of a 50% substitution rate, this single initiative can cumulatively mitigate 12,478.12 tCO₂ (accounting for 9.98% of total transport emissions), demonstrating immense mitigation potential.

Furthermore, this substitution strategy offers a significant temporal advantage. Driven by the deep decarbonization of the national power grid's energy structure (an increased proportion of green electricity) and continuous technological iterations in the underlying EV core systems, both the carbon emissions from power generation and the unit energy consumption of EV dump trucks will steadily decline. Consequently, their lifecycle emission reduction dividends will further expand in future engineering practices. Future research should consider integrating projected changes in grid emission factors to explore dynamic break-even calculations, thereby providing a more comprehensive evaluation of long-term electrification benefits.

4.4.2. Economic Feasibility of Equipment Electrification

While the environmental dividends of electrification are evident, its widespread adoption in engineering projects fundamentally hinges on its economic feasibility.

To evaluate the economic viability of pure electric versus diesel dump trucks, a Discounted Payback Period (DPP) model is formulated. Assuming the EV's lower residual value is offset by reduced maintenance costs over a 10-year lifespan, its initial capital premium is recovered exclusively through per-shift energy savings. This assumption aligns with current industry estimates for heavy-duty electric equipment, as the lack of an internal combustion engine substantially lowers routine servicing expenses [59]. Adopting this offsetting approach establishes a conservative scenario for our economic analysis, ensuring the financial viability of electrification is evaluated objectively without overstating its benefits. Factoring in the discount rate to account for the time value of money, the dynamic equilibrium equation is expressed as follows:

$$\Delta P = \sum_{t=1}^{T_{BE}} \frac{S_a \times \Delta C_e}{(1+r)^t} \quad (7)$$

in which, ΔP —initial capital premium, T_{BE} —break-even time in years, S_a —annual operational volume, ΔC_e —energy cost savings per machine-shift, t —specific calculation year, r —discount rate.

The break-even time can be expressed as:

$$T_{BE} = -\frac{\ln\left(1 - \frac{r \times \Delta P}{S_a \times \Delta C_e}\right)}{\ln(1+r)} \quad (8)$$

The break-even machine-shifts can be expressed as:

$$S_{\text{tot}} = S_a \times T_{\text{BE}} \quad (9)$$

To accommodate charging constraints and heavy-duty demands, 400 kWh and 600 kWh EV dump trucks are evaluated. Operational expenditure calculations utilize local energy prices to account for regional disparities. Given its long-term stability, a flat electricity rate of 0.7126 RMB/kWh is applied; conversely, to address geopolitical volatility, the current diesel price of 8.24 RMB/L serves as the baseline for a $\pm 10\%$ to $\pm 30\%$ sensitivity analysis. Following the Quota (which represents a typical, industry-average estimate), the annual operational volume is set to 200 machine-shifts. Incorporating the current LPR and a project risk premium, the discount rate (r) is established at 5%. The resulting break-even machine-shifts are presented in Figure 7.

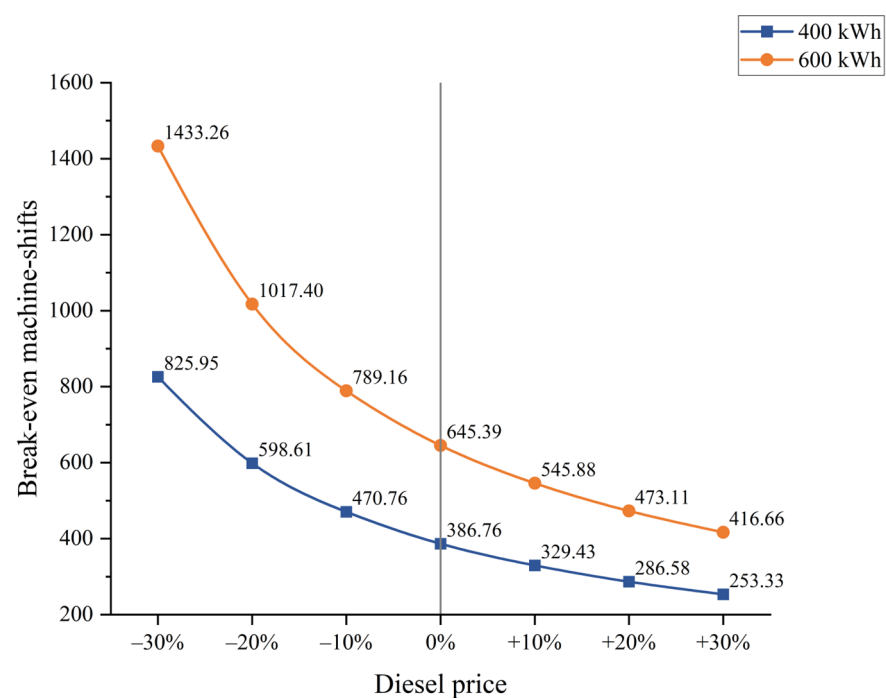


Figure 7. Break-even machine-shifts under varying diesel prices for EV dump trucks (400 kWh and 600 kWh).

Under the baseline diesel price, the break-even points for the 400 kWh and 600 kWh EV models are 386.76 and 645.39 machine-shifts, respectively, requiring merely 1.9 and 3.2 years to recover the initial capital premium. Even under the worst-case scenario of a 30% drop in diesel prices, the break-even points surge to 825.95 and 1433.26 machine-shifts; although the payback period for the 600 kWh model extends to 7.2 years, it remains within the vehicle's 10-year design lifespan.

Consequently, the pure electric substitution for dump trucks combines significant environmental mitigation dividends with high economic feasibility, fully validating the broad application prospects of equipment electrification in highway construction.

However, it is important to note that the findings regarding the electrification of the dump truck should be generalized with caution. The environmental and economic benefits of electrifying construction machinery and vehicles are sensitive to regional variables. The actual carbon mitigation potential in different areas may vary due to differences in regional power grid structures (such as the proportion of renewable energy). Given the geographical fluctuations in energy costs, the payback period may differ accordingly.

Furthermore, both aspects are affected by local climate conditions, which influence the operating conditions of electrified machinery and vehicles. Therefore, when extrapolating these results to other regions, local grid structures and prevailing energy market prices must be carefully considered.

4.5. Uncertainties and Limitations

It is important to acknowledge the inherent uncertainties associated with the LCA methodology applied in this study. Primary data on project-actual fuel and electricity usage could not be obtained because the construction contractor lacked comprehensive logs regarding specific energy consumption and exact subproject shift allocations for individual off-road machinery and transport vehicles. Coupled with the fact that the carbon accounting was conducted post-construction, on-site monitoring was rendered infeasible. Additionally, while renting key machinery and vehicles for experimental measurements of energy consumption and combustion emissions was considered, practical resource constraints made this challenging. Moreover, the age, mechanical wear, and specific working conditions of rented equipment might not fully align with the actual machinery deployed on-site, potentially introducing new uncertainties. Therefore, this study sourced emission factors from the CPCD/CLCD databases and adopted Quota-based energy consumption. Consequently, the major uncertainties in our accounting model primarily stem from two key aspects:

- **Emission Factors:** The reliance on generalized databases for material production, energy generation, and fuel combustion may not perfectly capture the specific regional, temporal, or technological characteristics involved in this project.
- **Energy Consumption Rates:** The energy consumption per shift for off-road machinery and transport vehicles was directly sourced from the latest Quota. These generalized rates may deviate from actual on-site consumption due to differences in equipment age, mechanical wear, varying operator behaviors, and complex geological or logistical conditions.

While these generalized assumptions are necessary for macro-level accounting and ensuring cross-project comparability, they inevitably introduce data variability. A limitation of the current study is the absence of a quantitative uncertainty analysis to evaluate the precise impacts of the aforementioned emission factors and consumption rates.

Finally, while the technical and economic feasibility of machinery electrification was discussed, detailed quantitative modeling of infrastructure costs, long-term battery degradation, and dynamic payload shifts falls outside our current scope. Specifically, a fully integrated quantitative assessment of these supporting components and operational variables was not conducted.

5. Conclusions

This study developed a life-cycle carbon emission accounting model for highway construction and conducted a high-resolution assessment based on an actual expressway project in the Central Plains. The research systematically reveals the heterogeneous distribution patterns of carbon emissions, outlines mitigation pathways, quantitatively validates the emission reduction benefits of four low-carbon technologies, and comprehensively evaluates the dual environmental-economic feasibility of core equipment electrification. The main conclusions are as follows:

1. Bridges and culverts serve as the primary “carbon hotspots” along the alignment. With merely 16.08% of the mileage, they contribute 40.09% of total emissions, driven by a precipitous emission intensity (12,613.87 tCO₂/lane-km). Subgrade engineering generates comparable total emissions. Pavement and traffic safety facilities account

for 12.87% and 6.40%, respectively; the latter, often overlooked in previous studies, proves non-negligible.

2. Highway construction is fundamentally “embodied-carbon-dominated.” Materials account for 89.44% of total emissions and exhibit extreme inequality: cement, steel, and quicklime cumulatively contribute 93.66% of the total material emissions due to their energy-intensive upstream processes.
3. Construction equipment emissions display distinct divergence patterns. The carbon emissions of off-road machinery exhibit profound “asymmetry” (e.g., mixing equipment is “low-shift, high-emission,” whereas winches are “high-shift, low-emission”). Conversely, transport vehicle emissions are highly concentrated and positively correlated with shift consumption, with dump trucks accounting for 92.15% of total transport emissions.
4. The marginal mitigation effects of traditional “reduction-oriented” strategies are diminishing, necessitating deep decarbonization across the supply chain. Given the high maturity of current highway design and construction systems, the potential to compress material and equipment consumption from the demand side is severely constrained. Driven by national energy conservation and carbon reduction action plans [60] and the inclusion of high-energy-consuming industries into the national carbon trading market [61], dual administrative and market mechanisms are compelling upstream high-carbon material production processes toward deep decarbonization. Meanwhile, stringent emission regulations and fierce market competition will continue to drive the optimization of combustion efficiency in traditional internal combustion engines.
5. During the construction phase, stakeholders should comprehensively advance low-carbon material substitution, solid waste recycling, and the pioneering electrification of equipment. The resin-bonded gravel sound barrier validated in this project (achieving a 73.26% emission reduction) demonstrates immense potential for widespread application across infrastructure networks. Regarding electrification, pure electric dump trucks at a 50% substitution rate can reduce total transport emissions by 9.98%. The DPP evaluation indicates that even for a 600 kWh model catering to “charging-constrained, heavy-duty per shift” scenarios, the initial capital premium can still be safely recovered within its lifespan under an extreme stress test of a 30% diesel price plunge. The severe volatility of fossil fuel prices triggered by geopolitical conflicts exacerbates infrastructure cost risks, objectively accelerating this comprehensive electrification transition.

In this context, alongside continuous iterations in materials science and new energy technologies, future research should prioritize primary data collection to address existing uncertainties and integrate key technical parameters. This approach will provide a more robust, confidence-bounded assessment of highway construction carbon footprints. Furthermore, subsequent studies will expand into the systematic evaluation of diverse novel low-carbon materials and conduct a holistic, dynamic, and life-cycle-based feasibility evaluation of fully electrified construction equipment, aiming to provide comprehensive theoretical support for deep decarbonization in transport infrastructure.

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