Original Research Article

New quality productivity enables the construction path of near zero carbon service areas on expressways

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Abstract: Global climate change is driving the green and low-carbon transformation of transportation systems, with highway service areas—energy-intensive nodes—urgently requiring near-zero carbonization. This study introduces the New Quality Productivity Theory and constructs a three-dimensional theoretical framework of "technology-institution-governance" to systematically analyze its mechanisms in building near-zero carbon highway service areas. Implementation strategies are proposed, including phased construction, talent cultivation, data platform development, and policy optimization. The findings not only enrich the theoretical application of New Quality Productivity but also provide practical references for the green transformation of transportation infrastructure.

Keywords: New quality productivity; Expressway service area; Near zero carbon; Low carbon transition

1. Introduction

With the growing severity of global climate change, advancing the green and low-carbon transformation of transportation systems has become a crucial pathway for achieving the "dual-carbon" strategic goals[1]. As key nodes in the transportation network, highway service areas not only provide essential transportation services but also face the challenges of high energy consumption and intensive carbon emissions. Promoting the transition of service areas toward a "near-zero-carbon" model is therefore not only a critical link in building a green transportation system but also an important breakthrough for fostering the coordinated development of urban–rural green infrastructure and constructing a sustainable transportation ecosystem[2]. The concept of "New Quality Productivity," a key idea within the process of Chinese modernization, emphasizes the driving roles of green energy, digital technology, and institutional restructuring in promoting high-quality socio-economic development[3]. Applying this concept to the green transformation of highway service areas not only extends the practical boundaries of the theory but also provides new perspectives and approaches for upgrading green infrastructure[4].

2. Theoretical logic of new quality productivity empowering near-zero-carbon highway service areas

New Quality Productivity, through technological innovation, institutional design, and governance optimization, provides both theoretical foundations and practical pathways for the near-zero-carbon transition of highway service areas [5]. **Technological empowerment** enhances resource allocation efficiency and enables low-carbon operations through digitalization, intelligent systems, and green energy technologies. **Institutional empowerment** offers policy frameworks, economic incentives, and regulatory standards that support technology adoption and management innovation. **Governance empowerment** highlights multi-actor collaboration, where governments, enterprises, research institutions, and the public interact to achieve systemic and efficient low-carbon construction [6]. The interplay of these three dimensions—technology, institutions, and governance—together constructs the theoretical logic framework for building near-zero-carbon highway service areas (see **Figure 1**), which provides a clear analytical pathway for subsequent research.

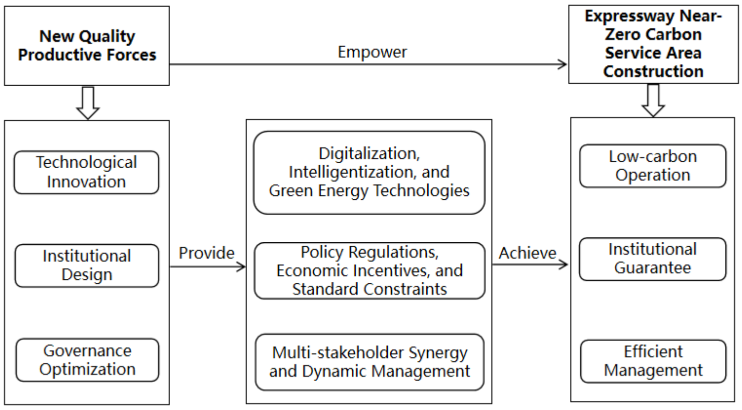

Figure 1. Theoretical logical framework of high-quality productivity enabling the construction of near-zero carbon service areas on expressways.

3. Practical challenges in applying new quality productivity

3.1. Technological bottlenecks in application and integration

At the technical level, photovoltaic systems, energy storage, and intelligent dispatching have become core solutions for near-zero-carbon service areas, yet their integration and effectiveness remain limited. For example, the Xianshan Service Area in Jiangsu deployed a 2.8 MWp distributed photovoltaic system with supporting storage, theoretically sufficient for daily electricity needs. However, during peak hours of EV charging, supply fluctuations persisted, and dispatching capacity was insufficient to absorb peak demand. Similarly, the distributed solar-storage project on the Panzhihua–Dazhou Expressway in Sichuan achieved an annual output of 4.22 million kWh, but issues of grid stability and lack of mature standards for integration with charging facilities remain. These cases demonstrate that while technologies are promising, barriers to large-scale promotion and cross-regional integration still need to be overcome.

3.2. Institutional gaps in design and implementation

Institutional empowerment faces challenges in both design and execution. Current low-carbon policies and incentives often target single technologies or stages, lacking systemic planning and interdepartmental coordination, which limits policy effectiveness. For instance, Henan Transportation Investment Group developed China's first "zero-carbon service area cluster," establishing 42 standards covering energy, ecology, and management, and achieved energy self-sufficiency with an 18.46 MWp photovoltaic system and 10,179 kWh of storage. While valuable, these standards remain at the enterprise level and have not been elevated to national norms. Similarly, the Jinan East Service Area in Shandong achieved an annual reduction of 3,410 tons of CO_2 emissions, but the reductions have yet to be incorporated into market-based carbon trading mechanisms, limiting economic benefits and reflecting institutional shortcomings.

3.3. Governance challenges in multi-stakeholder collaboration

The complexity of multi-actor coordination constrains governance efficiency. For example, Henan's "virtual power plant" model can generate additional annual revenue of around 800,000 RMB through energy interconnection, but requires tight collaboration among governments, grid operators, service area managers, and energy firms, making implementation difficult. At the Xianshan Service Area in Jiangsu, "all-electric kitchens" and water-saving retrofits involved multiple actors, including catering vendors, designers, and managers, where unclear responsibilities delayed progress. Sichuan's attempt to integrate "near-zero-carbon + transport–tourism" demonstration areas likewise revealed coordination difficulties across tourism, transportation, and energy departments, underscoring the need for more robust cross-sector governance mechanisms.

3.4. Contradictions between resource integration and cost control

Significant tension exists between high upfront investment and long-term returns. Henan's "zero-carbon service area cluster" achieved 100% energy self-sufficiency and generated 19.42 million kWh annually through AI-based scheduling, exceeding local demand. Yet without financial tools such as carbon trading or green credit, the payback period remains long. The Xianshan Service Area saves about 370,000 RMB annually in electricity costs through photovoltaics, but returns are still limited relative to the total retrofitting investment. Similarly, Sichuan's efforts to establish hydrogen fueling stations and heavy-truck battery swapping corridors face high capital costs and unstable utilization rates, highlighting contradictions in resource integration and cost control.

3.5. Risks in information and data management

Widespread application of digital and intelligent technologies increases service areas' dependence on data, raising risks in security and management. Henan's smart energy management platform optimizes generation, storage, and charging at the cluster level, but sensor delays or data errors could cause scheduling imbalances and disrupt operations. At Xianshan, inconsistent standards in water recycling and energy monitoring data restricted cross-regional sharing and integration. In Sichuan, pilot projects linking virtual power plants with electricity markets required traffic flow, power, and trading data, raising urgent concerns about data security and privacy protection.

4. Pathways for building near-zero-carbon highway service areas empowered by new quality productivity

Guided by the theoretical framework, construction should advance in phased and systematic steps—pilot exploration, institutional refinement, collaborative promotion, resource optimization, and intelligent operation. These are translated into actionable pathways across the three dimensions of technology, institutions, and governance, following the logic of "technology-driven – institution-secured – governance-coordinated" to integrate low-carbon operation, green facilities, and smart management.

4.1. Technology-driven pathway

Adopt "solar–storage–charging integration + smart dispatching" by deploying distributed photovoltaics, wind power, and storage facilities, integrated with EV charging, battery swapping, and hydrogen fueling. Incorporating AI forecasting and virtual power plant platforms can shift service areas from "single-site pilots" to "regional collaboration," optimizing energy structures and enhancing life-cycle efficiency.

4.2. Institution-secured pathway

Institutional innovation is essential for technology deployment. Establish unified standards for energy use, carbon emissions, and green operations, while linking them to carbon trading and green finance. Policies such as green credit and tax incentives can mobilize private capital, reduce risks, and ensure returns, thereby laying the foundation for sustainable low-carbon development.

4.3. Governance-coordinated pathway

Build multi-level collaboration across government, enterprises, research institutions, and the public. Governments provide policy and oversight, enterprises lead construction and operations, researchers conduct evaluations and optimizations, while consumers reinforce outcomes through green choices. Future efforts may leverage PPP models and participatory governance to shift from “top-down promotion” to “co-governance and sharing,” fostering a sustainable collaborative framework.

4.4. Resource and data pathway

Innovative financing mechanisms such as green funds, carbon finance, and energy performance contracting can address the tension between high investment and long payback. Simultaneously, developing national-level smart energy data platforms will enable cross-regional monitoring, carbon accounting, and dynamic scheduling, improving efficiency. Once interconnected nationwide, these systems can support data-driven, efficiency-oriented management models that sustain long-term green transformation.

5. Conclusion

New Quality Productivity provides a replicable and scalable framework for constructing near-zero-carbon highway service areas. It enriches research perspectives on green transportation and low-carbon infrastructure while offering theoretical and practical solutions for achieving the “dual-carbon” goals and high-quality transportation development. However, challenges remain, including insufficient technological integration, fragmented institutional standards, difficulties in cross-sector collaboration, and underdeveloped financing mechanisms. Future work should strengthen cross-regional smart energy platforms, improve policy tools such as carbon finance and green credit, advance standardized institutional systems nationwide, and deepen industry–academia–research collaboration to enhance the synergy between technological innovation and governance models.

Funding

2025 Yueyang Social Science Research Project “Research on New Quality Productivity Empowering Low-carbon Transformation of Yueyang Expressway” (Project No.: 2025Y253).

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References

[1] Zhang, J. (2024). Research on the impact of digitalization on green development: An empirical analysis from the low-carbon strategy perspective. PLOS ONE, 19(3), e0300288.

[2] Liu, Y., & Wang, H. (2025). Low-carbon pathways to digitalization: Can the digital economy promote carbon efficiency? Frontiers in Environmental Science, 13, 1567395.

[3] Research Institute of Economy, Trade and Industry (RIETI). (2024). China’s vision for promoting “new quality productive forces.” RIETI China Update.

[4] China Briefing. (2024). China’s new quality productive forces: An explainer. China Briefing.

[5] Lv, H., Lian, Y., & Hua, X. (2025). The relationship between FDI quality, new quality productive forces, and economic resilience in China’s Yangtze River Delta region. Humanities and Social Sciences Communications, 12, 1083.

[6] Chen, Z., & Li, Q. (2024). New quality productivity and industrial structure in China. Sustainability, 16(16), 6796.