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Pathways for the Digital-Intelligent Transformation of Expressways Toward a Value Ecosystem

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Abstract

Expressways are evolving from single toll corridors toward a value ecosystem integrating traffic services, industrial development and network synergy, and digital-intelligent transformation provides the opportunity for this transition, though the implementation pathways remain unclear. On the basis of a systematic review of the evolution of road value and the status of digital-intelligent development in the industry, this paper identifies four dilemmas: insufficient value perception, crude traffic diversion, homogeneous derived businesses, and inadequate road-network synergy; and then proposes four pathways: dynamic assessment, precise traffic diversion, digital-intelligent development of scenarios, and collaborative value-added creation, corroborated by national toll road statistical bulletins and typical cases such as differentiated tolling and smart service areas. The study shows that the core of digital-intelligent transformation lies in connecting the value chain of value measurement, precise allocation, scenario monetization and network amplification with data as a key production factor, and that the four dilemmas and four pathways constitute a closed loop from diagnosis to intervention, providing a decision-making reference for operating enterprises to release the three layers of road value, namely road-based value, road-derived value and road-network value.

Keywords

Expressway; Road Value; Digital-intelligent Transformation; Value Ecosystem; Transformation Pathway.

1. Introduction

Expressways are the backbone of the national comprehensive transportation system and have long relied on toll collection as their single source of value. By the end of 2024, the total length of the national highway network reached 5.4904 million km, of which expressway mileage reached 190,700 km, an increase of 7,000 km over the previous year-end, and the national expressway network reached 124,100 km, ranking first in the world [1]. However, with the densification of the road network and the slowdown of traffic growth, the traditional operation logic of building first and collecting later has become difficult to sustain. According to the 2023 Statistical Bulletin on National Toll Roads, by the end of 2023 the national toll road mileage reached 171,100 km, of which expressways accounted for 142,800 km; the year-end debt balance reached 6,153.53 billion yuan, annual toll revenue was 593.79 billion yuan, while total expenditure was as high as 1,078.77 billion yuan, resulting in a revenue-expenditure gap of 484.98 billion yuan [2]. Relying solely on toll revenue can no longer cover the rigid expenditures of debt repayment, maintenance and operation management, making the need for off-road compensation increasingly urgent.

Meanwhile, new-generation information technologies represented by big data, artificial intelligence and vehicle-infrastructure cooperation are penetrating the highway sector at an accelerating pace. In September 2023, the Ministry of Transport issued the Opinions on Promoting Digital Transformation of Highways and Accelerating the Development of Smart Highways, proposing that significant progress be made in highway digital transformation by 2027 and that full digital transformation be achieved by 2035, with both a physical highway system and a digital twin highway system being built[3]. By the end of 2024, more than 4,000 km of highways had completed intelligent upgrading, and smart expressway construction has moved from scattered pilots toward systematic integration and large-scale application. Digital technologies provide a new opportunity for reshaping the way expressway value is created; however, how digital-intelligent transformation can be substantively translated into systematic improvement of road value still lacks a clear pathway in practice, and some sections suffer from the dilemma of digitalization for its own sake, with inputs that are difficult to quantify in terms of returns.

On the basis of sorting out the evolution of the connotation of expressway road value and the status of digital-intelligent development, this paper identifies the main dilemmas facing the current transformation, and then proposes specific digital-intelligent pathways for enhancing road value, aiming to provide a reference for operating enterprises to seize the opportunities of digital transformation and release multi-layered road value.

2. Literature Review

Research on expressway value assessment is the foundation of road-derived economy and digital transformation studies. Su and Yang[4] constructed an expressway value prediction and correlation analysis model based on grey system theory, and, taking Fujian Expressway as the research object, identified key value-influencing factors such as maintenance cost and operating revenue, providing a methodological basis for quantitative value management. Liu et al.[5] constructed a sustainable operating benefit identification model for smart expressways from the stakeholder perspective, integrating One-Hot encoding and a deep neural network (the OH-D model), with an identification accuracy of 96.1%, providing an analytical tool for benefit prediction in the early stage of projects. Fang[6] proposed a calculation method for road network travel time value benefits from a network perspective and verified the feasibility of road-network-level time value assessment using the Guangdong expressway network as an example. Overall, existing studies mostly focus on a single value dimension and have not yet formed a systematic integration framework for the three layers of road-based, road-derived and road-network value.

Smart expressway is a research hotspot in the transportation field in recent years. Cen et al.[7] systematically constructed the technical system of smart expressways, proposed the three-network integration intelligent infrastructure and the cloud-edge-terminal collaborative cloud-control platform architecture, distilled a technology set consisting of 3 categories, 5 subsets and 33 technologies, and applied it to the design of the Hangzhou-Shaoxing-Ningbo smart expressway. Weng et al.[8] defined the connotation of the digital foundation of expressways from the perspective of an operating system, proposed the overall architecture of cloud, network, map, data and intelligence, and the 1.0 to 3.0 evolution forms, providing an architectural paradigm for road-domain digital transformation. In international research, Pompigna and Mauro[9] systematically reviewed technological innovations in the field of smart roads and pointed out the potential of intelligent infrastructure in improving traffic efficiency and safety; Liu et al.[10] proposed the basic characteristics and overall framework of the new-generation smart highway, emphasizing the synergistic evolution of vehicles and road systems; Anthi et al.[11] reviewed the application of artificial intelligence in smart highways, covering scenarios such as automatic incident detection, traffic prediction and digital twins, while also pointing out challenges in data security and technical standards. The above studies have laid a technical foundation for the digital-intelligent release of road value, but most focus on technological implementation and pay limited attention to the design of value-conversion pathways.

Road-derived economy and differentiated tolling are important policy instruments for addressing the imbalance of expressway revenue and expenditure. Wang et al.[12] systematically analyzed the environment for the comprehensive development of the road-derived economy of expressway service areas using the PEST model, and proposed the development suggestions for six types of characteristic service areas: comprehensive commercial, tourism and leisure, logistics, passenger transport, energy integration, and open and shared. In terms of industry practice, by the end of 2022, there were about 3,546 pairs of expressway service areas nationwide, with operating revenue exceeding 198 billion yuan; however, refined oil business accounted for as much as 92%, non-oil business only 8%, and about 30% of service areas were in a loss-making state[12], indicating huge room for mining road-derived value. On the tolling side, Wu et al.[13] systematically reviewed the background, implementation methods and key technologies of differentiated expressway tolling; the Wenzhou practice shows that after implementing differentiated tolling for Class 1 passenger cars with ETC cards with the Zhejiang C license plate, the average daily traffic volume in the early stage increased by more than 23% compared with that before tolling, and the exit volume at toll stations such as Yaoqi and Airport West increased by more than 30%[14].

In summary, existing studies have accumulated a solid foundation in value assessment, smart technology, road-derived economy and toll mechanisms, but three deficiencies remain. First, value research mostly stays at a single pathway level and lacks systematic integration of perception, diversion, operation and synergy. Second, dilemma identification and countermeasure proposals are mostly qualitative descriptions, with insufficient quantitative evidence and typical case mining. Third, policy research and technical research are relatively disconnected, and macro-institutional constraints are rarely incorporated into transformation pathway design. On the basis of absorbing the above achievements, this paper constructs a closed-loop framework of dilemmas and pathways, and corroborates it with authoritative statistical bulletins and typical case data, striving to make progress in both research framework and empirical support.

3. Evolution of Expressway Road Value and Status of Digital-Intelligent Development

3.1. Evolution Logic of the Connotation of Road Value.

From the perspective of value forms, expressway road value has evolved from single to multiple dimensions. In the early stage, expressways mainly undertook the transport function of connecting cities and regions, and their value was concentrated in basic functional dimensions such as traffic capacity, driving safety and time-saving, namely road-based value. With the formation of the road network and the development of the economy and society along the routes, the added value formed by service area operations, roadside development and industrial agglomeration along the routes that rely on expressway alignment resources has become increasingly prominent, constituting road-derived value. Furthermore, when multiple expressways are connected into a network, the overall benefits brought by their role as network nodes, such as transport organization efficiency, regional economic radiation and multimodal transport synergy, continue to be released, forming road-network value that is higher than the arithmetic sum of single lines[6]. Thus, road value has expanded from a relatively single transport corridor function to a value ecosystem with road-based value as the foundation, road-derived value as the increment, and road-network value as the synergy.

This evolution process is mutually corroborated by the shift in the industry investment structure. In 2023, the national highway fixed-asset investment reached 2,824 billion yuan, of which expressways completed 1,595.5 billion yuan; in 2024, highway fixed-asset investment was 2,577.4 billion yuan, and expressways completed 1,401.5 billion yuan, a year-on-year decrease of 12.2%[1]. Against the background of slowing construction investment and a huge stock road network, the focus of value creation for operating enterprises is shifting from incremental construction to stock operation, and digital-intelligent transformation has become the key lever for leveraging stock value. Table 1 shows the changes in the scale and investment of the national expressway network in recent years.

Table 1. Scale and Investment of the National Expressway Network, 2022 to 2024

Indicator	2022	2023	2024
Expressway mileage / 10,000 km	17.73	18.36	19.07
New mileage in the year / 10,000 km	0.82	0.64	0.70
National expressway mileage / 10,000 km	11.99	12.23	12.41
Highway fixed-asset investment / 100 million yuan	28527	28240	25774
Of which: expressway investment / 100 million yuan	16262	15955	14015

3.2. Status of Digital-Intelligent Development of Expressways.

In recent years, the digital-intelligent level of the expressway industry has continued to improve, laying the technical conditions for the release of road value. In terms of data collection, perception facilities are increasingly complete: the electronic toll collection (ETC) system and gantry systems have achieved full network coverage and can continuously collect traffic flow data by section, vehicle type and time period. Combined with the continuous deployment of sensing equipment such as video surveillance, meteorological and environmental monitoring, axle load and maintenance monitoring, a data resource with considerable scale and fine granularity has been formed. In terms of operation decision-making, machine-learning-based short-term traffic flow prediction, congestion warning and differentiated tolling pilots have been implemented on some sections, and some operating enterprises have applied them to holiday traffic protection, incident handling and tolling strategy adjustment, showing considerable potential for improving quality and efficiency. In terms of service level, smart service areas improve travel experience and operating benefits through passenger flow monitoring, parking guidance, online commerce and membership operations. In terms of network synergy, multimodal transport and regional platform construction are advancing steadily, and information connectivity between highways and railways and waterways is continuously strengthened. In 2024, the national highway passenger flow reached 59.290 billion person-trips, a year-on-year increase of 4.8%, of which passenger car travel reached 47.509 billion person-trips, and the data value of massive travel flow has become increasingly prominent[1].

In terms of demonstration projects, smart expressway construction has shifted from pilots to large-scale promotion. At the end of 2017, Zhejiang launched the construction of the Hangzhou-Shaoxing-Ningbo smart expressway with a total length of about 170 km, applying the three-network integration and cloud-edge-terminal collaborative architecture to carry out innovative services such as lane-level management and control, free-flow tolling and autonomous driving truck platooning[7]; in September 2023, the Jiwei section of the Jinan-Qingdao Central Line opened to traffic, becoming the first zero-carbon smart expressway in China; at the end of the same year, the reconstruction and smart expressway project of the Ningwu Expressway in Anhui was completed and opened, building a five-intelligence-in-one smart expressway architecture and realizing proactive safety warning and accompanying information services. These practices show that digital-intelligent transformation has moved from single-technology verification toward systematic integration, providing replicable engineering models for the release of road value.

4. Realistic Dilemmas of Digital-Intelligent Transformation

4.1. Insufficient Value Perception.

Expressway operation involves multiple businesses such as tolling, traffic surveys, maintenance and operation, and data are scattered across multiple systems with inconsistent standards, inconsistent calibers and even mutual fragmentation. Lacking a unified measurement of road value across the whole network and across multiple dimensions, operating enterprises can hardly answer the basic questions of how large the road value is now, where the shortcomings lie, and how much room there is for improvement. With an unclear value base, digital-intelligent improvement lacks clear basis and targets, and it is easy to fall into the dilemma of digitalization for its own sake, with inputs that are difficult to quantify in terms of returns. In fact, in 2023, the toll revenue-expenditure gap of national toll roads reached 484.98 billion yuan, with maintenance expenditure of 82.59 billion yuan and operation management expenditure of 75.81 billion yuan[2]. If a refined value assessment system cannot be established, capital allocation can hardly achieve optimal benefits, and the dual pressure of debt and operation will continue to accumulate. More importantly, the absence of value measurement will also cause resource misallocation, concentrating limited digital-intelligent inputs on links that deliver quick results but make little value contribution, while sections and scenarios with real value-added potential receive no support, and the transmission chain between transformation inputs and value returns is systematically blocked.

4.2. Crude Traffic Diversion Measures.

On the traffic flow side, many sections are still in a state of passively waiting for passenger flow, lacking effective prediction and induction means during congested periods, and differentiated tolling is mostly a crude unified discount that fails to precisely implement policies according to real-time traffic flow and user demand. Taking Wenzhou as an example, its early differentiated tolling scheme only reduced tolls for Class 1 passenger cars with ETC cards with the Zhejiang C license plate, with a limited scope of beneficiaries and no significant diversion effect on driving groups with low price sensitivity, and the congestion of Ouhai Avenue during peak hours was not obviously alleviated[14]. With passive passenger flow and crude supply, the traffic capacity and toll resources of sections have not been fully exploited. On the one hand, congestion during holidays and peak hours leads to a decline in traffic efficiency, and potential traffic demand is forced to shift to parallel national and provincial highways, damaging both toll revenue and travelers' time cost; on the other hand, the idle traffic capacity during off-peak hours lacks price signals to guide demand, resulting in structural waste of road network resources. The superposition of the two leaves obvious room for improving traffic value.

4.3. Homogeneous Derived Businesses.

On the derived business side, service area commercial development generally suffers from homogeneity and templating, with one style for a thousand areas, lacking high-potential scenario identification and differentiated layout based on industrial characteristics and passenger flow data along the routes. Among about 3,546 pairs of service areas nationwide, about 30% are in a loss-making state, and in the revenue structure refined oil business accounts for as much as 92%, with negligible profit contribution from non-oil businesses[12]. The roadside land, location and commercial resources relying on traffic flow have not been transformed into sustainable operating revenue. The reasons are threefold. First, business decisions lack data support, and service area format selection mostly relies on experience replication, making it difficult to fit the customer structure and consumption characteristics of the sections involved. Second, roadside resource development is scattered, and derived formats such as photovoltaics, logistics and cultural tourism lack synergy with the main traffic business, resulting in a short value chain. Third, there is a lack of systematic collection and mining of passenger flow and consumption data, so refined operation is impossible, and operators can neither see the demand clearly nor measure the returns accurately. The development of road-derived value still remains at a relatively low level.

4.4. Inadequate Road-Network Synergy.

Under the current one road, one company management system, each section (company) tends to maximize its own revenue, and phenomena such as vehicles detouring across sections and information not being shared occur from time to time, forming section silos. At the same time, information gaps still exist in multimodal transport connections, and the transshipment, early warning and coordinated scheduling among highways, railways and waterways are not smooth enough, making it difficult to fully release the overall transport organization efficiency and radiation value of the regional road network. In 2024, the national port container rail-water intermodal transport volume reached 11.55 million TEU, a year-on-year increase of about 16.5%, but its share of total port container throughput is still low, and the inadequacy of road-network synergy restricts the realization of road-network value, a high-level value. From the mechanism perspective, cross-section synergy also faces obstacles such as unclear revenue distribution and unclear data ownership, and the local optimum of a single section often conflicts with the overall optimum of the road network. Coupled with the lack of a unified cross-section scheduling platform and benefit coordination mechanism, network-based synergy can hardly form spontaneously, and road-network value has long been in a state of being undervalued and wasted.

5. Digital-Intelligent Pathways for Enhancing Road Value

5.1. Dynamic Assessment Pathway

To address the problem of insufficient value perception, a dynamic road value assessment system should be built based on multi-source data fusion. By aggregating multi-source data such as tolling, traffic surveys, maintenance and operation, unifying data calibers, constructing a multi-dimensional evaluation index system covering road-based, road-derived and road-network value, and combining subjective-objective combined weighting with comprehensive evaluation models, the road value of the whole network and of single sections can be dynamically measured and monitored. Existing studies show that grey correlation analysis can effectively identify the main value-influencing factors[4], and deep neural networks can realize high-accuracy identification of operating benefits based on stakeholder cognition[5], providing mature methodological tools for value assessment. At the implementation level, a section-level value database can be established first and then gradually expanded to the network level, forming monthly or quarterly dynamic value reports so that assessment results are truly embedded in the business decision process; at the same time, value benchmarks can be set against benchmark sections in the industry, so that the evaluation results reflect both one's own progress and the gap with the advanced level. The core mechanism of this pathway is to make the value base explicit and quantifiable, use the evaluation results to identify value shortcomings and improvement potential, and provide scientific basis and target guidance for the implementation of each enhancement pathway, avoiding blind investment, which is the foundation for the precise implementation of the other three pathways.

5.2. Precise Traffic Diversion and Differentiated Operation Pathway.

To address the problem of crude traffic diversion measures, precise traffic diversion should be realized based on traffic flow big data and artificial intelligence prediction technology. Through machine learning for short-term prediction of traffic flow by time period and section, congested and idle resources are identified, and differentiated tolling by time period and section, dynamic pricing and proactive induction and scheduling are implemented accordingly, guiding vehicles to stagger peak hours and improving the balance and overall flow of road network traffic. The practical effects of differentiated tolling have been verified in many places: the differentiated tolling scheme designed for the Longqing Expressway in Shandong based on a bi-level programming model can increase the operating revenue in the north-south direction by 7.8619 million yuan per year and reduce travelers travel costs by 7.1651 million yuan per year[15]; in Wenzhou, Zhejiang, the average daily traffic volume increased by more than 23% in the early stage of the implementation of differentiated tolling in the urban area[14]. At the same time, relying on user portraits and travel data analysis, service supply can be optimized, and differentiated tolling and service combinations can be designed for different customer groups such as commuters, freight and tourism, improving user stickiness and road network utilization. In terms of implementation rhythm, the principle of pilot first and promotion later should be followed, and the discount intensity, time period and objects of differentiation should be dynamically evaluated and iterated to avoid the loss of revenue caused by a one-size-fits-all policy. The core mechanism of this pathway is to replace experience-based judgment with data-driven decision-making, change from passively waiting for passenger flow to actively attracting traffic, and realize the dual improvement of toll revenue and road utilization efficiency while thickening traffic value.

5.3. Digital-Intelligent Development of Scenarios Pathway for Road-Derived Businesses.

To address the problem of homogeneous derived businesses, high-potential scenarios for road-derived development should be identified with data to promote the diversified release of road-derived value. Using location, passenger flow, industry and consumption data, the commercial value of service areas and areas along the routes should be accurately assessed, and scenarios such as digital commerce in service areas, new-energy photovoltaic and energy storage facilities, logistics nodes and takeoff and landing points for the low-altitude economy should be laid out in a differentiated manner; through online-offline integrated operation, traffic flow should be transformed into consumption and industrial flow, extending the value chain. At the implementation level, passenger flow, industry and consumption data around service areas can be surveyed first to identify high-potential formats, and then the model can be validated through pilot service areas and gradually promoted to the whole network, forming a data-driven closed loop for road-derived development; at the same time, cooperation with local governments and industrial capital should be emphasized, using service areas as leverage to drive the coordinated development of land and industries along the routes and amplify the spillover effect of the road-derived economy. Industry benchmark practices show that after the overall upgrading and renovation of the Sutong Bridge Service Area in Jiangsu, the average daily turnover increased by 229% year-on-year and the profit of the year increased by 226%; the Dahuai Service Area in Guangdong combined overseas-Chinese hometown culture to build an open cultural, commercial and tourism complex, becoming the new gateway of Enping City[12]. Table 2 lists the practical outcomes of the road-derived development of typical service areas. The core mechanism of this pathway is to change from standardized replication to data-driven customization, precisely match the resource endowments and market demand along the routes, revitalize the dormant roadside resources into sustainable operating revenue, and cultivate a second growth curve beyond toll revenue.

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Table 2. Practical Outcomes of Road-Derived Economy Development of Typical Service Areas

Service area	Route / Province	Development model	Practical outcome
Meicun	Shanghai-Nanjing Exp. / Jiangsu	Tourism service complex	Over 120,000 person-trips/day at holiday peaks
Sutong Bridge	Shenyang-Haikou Exp. / Jiangsu	Overall upgrading and renovation	Daily turnover +229%, profit +226% year-on-year
Dahuai	Kaiyang Exp. / Guangdong	Overseas-Chinese culture commercial and tourism complex	New gateway of Enping, driving regional consumption
Lengshui	Shanghai-Chongqing Exp. / Chongqing	Eco-tourism RV campsite	First self-driving campsite of China expressways
Fangmaoshan	Shanghai-Nanjing Exp. / Jiangsu	Dinosaur-themed service area	Thematic diversion, linkage with 5A scenic area

5.4. Collaborative Value-Added Creation Pathway for Road-Network Synergy.

To address the problem of inadequate road-network synergy, network-level data sharing and cross-section joint operation should be promoted to release the superimposed value of the network. Relying on a regional road network data platform, the information silos of single sections should be broken to realize the interconnection of data such as traffic flow, road conditions, maintenance and accidents; through cross-section joint scheduling, coordinated diversion and integrated information services, the overall transport organization efficiency of the region should be optimized; and the information connection and coordination of multimodal transport among highways, railways and waterways should be strengthened to promote the circulation of factors in regional economic integration. The construction of the digital foundation is the technical premise of this pathway, and the industry has proposed the overall architecture of cloud, network, map, data and intelligence and a phased evolution route[8]. At the mechanism level, the design of cross-section revenue distribution and data rights confirmation rules should be advanced simultaneously, and the coordination difficulties under single-road competition should be resolved through joint operation agreements and provincial-level coordinated platforms, so that participating sections can share the incremental revenue brought by network value-added, forming an incentive-compatible synergy pattern. The core mechanism of this pathway is to transform single-road competition into win-win road network cooperation, upgrading road value from the simple accumulation of single lines to the overall amplification of networked synergy, and realizing high-level road-network value.

6. Conclusion and Outlook

The core of digital-intelligent transformation of expressways lies in the reconstruction of the value logic. Based on the evolution law of the three layers of road value, namely road-based, road-derived and road-network value, this paper identifies four dilemmas: insufficient value perception, crude traffic diversion, homogeneous derived businesses and inadequate road-network synergy, and proposes four pathways: dynamic assessment, precise traffic diversion, digital-intelligent development of scenarios and collaborative value-added creation. The four dilemmas and the four pathways constitute a closed loop from diagnosis to intervention: dynamic assessment answers where the value is, precise traffic diversion answers how to enlarge the value, scenario development answers how to monetize the value, and collaborative value-added creation answers how to amplify the value, jointly forming a systematic transformation framework from value quantification to precise realization and then to network value-added.

Looking to the future, with the deepening of highway digital transformation during the 15th Five-Year Plan period, the role of data as a production factor in road value creation will become more prominent. Operating enterprises should accelerate the construction of a unified data foundation and value measurement system, promote the evolution of differentiated tolling from static discounts to dynamic pricing, cultivate differentiated road-derived business formats based on roadside resource endowments, and deepen cross-section and cross-mode coordination with regional road network platforms as the link. The pathway framework proposed in this paper is still a directional exploration, and subsequent research can carry out empirical tests with the operating data of specific sections, further quantify the contribution elasticity of digital-intelligent inputs to road value, and provide a more solid basis for precise industry policy-making.

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