

Functional Architecture and Technical Path of the Intelligent-driven Traffic Safety Management System for Highway Reconstruction and Expansion

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Abstract: Digital and intelligent transformation is the key direction for China's transportation sector during the period of the 15th Five-Year Plan. To address the challenges of insufficient digital technology application, unclear system functional positioning, and unclear technical path in traffic safety management and control for highway reconstruction and expansion projects, this paper focused on small-scale, micro-scenarios, examining the functional architecture, technical path, and typical case studies of a digitally driven highway reconstruction and expansion traffic safety management and control system. Based on risk management and systems engineering theory, this paper analyzed five key characteristics of traffic safety in highway reconstruction and expansion projects. Based on the needs of typical business scenarios, a process-oriented structured analysis approach was employed to propose a functional architecture for a digital highway reconstruction and expansion traffic safety management and control system, and a technical path for digital highway reconstruction and expansion traffic safety management and control adapted to these scenarios and functions was constructed. Using a case study approach, this paper explored the current application of digital technology in highway reconstruction and expansion traffic safety management and control, as well as areas for optimization and improvement. The results indicate that a digitally driven highway reconstruction and expansion traffic safety management and control system should possess five key functions: data acquisition and processing, real-time traffic safety status diagnosis, traffic safety risk status prediction, decision-making and control, and data description and refined display. Currently, the functional completeness of digital highway reconstruction and expansion systems in China is approximately 80%. Traffic safety status diagnosis and traffic safety risk prediction are key areas for future optimization and improvement of highway reconstruction and expansion traffic safety management and control systems. The research results can provide theoretical guidance and technical support for the application of digital technology in traffic safety assurance in highway reconstruction and expansion, and help the digital transformation and upgrading of highway transportation infrastructure.

1. INTRODUCTION

With economic and social development, the contradiction between China's growing travel demand and the limited capacity of highway lanes has become increasingly prominent. Statistics from the Ministry of Transport show that the total length of highway reconstruction and expansion projects currently under construction in China exceeds 5,000 km, with a total investment exceeding RMB one trillion yuan^[1]. Obviously, highway reconstruction and expansion projects have become an important battlefield for China's economic and social development, and a new normal in the construction of highway transportation infrastructure for the present and a certain period in the future. New normal brings new risks. To ensure smooth traffic, China's highway reconstruction and expansion projects mostly adopt the mode of "construction while maintaining traffic flow", which possesses the dual characteristics of both highway operation and construction periods, leading to intertwined and superimposed construction safety and traffic safety risks, making the traffic system more complex and fragile. Studies have shown that compared with normal operating highway sections, the traffic safety risk of reconstruction and expansion projects increases by more than 30%^[2]. Therefore, how to ensure traffic safety in highway reconstruction and expansion projects is an urgent issue to be addressed.

In the context of digitalization and intellectualization, adopting digital-intelligent management and control technologies to solve the prominent traffic safety problems under the "construction while

maintaining traffic flow” mode of highway reconstruction and expansion is an inevitable choice. From the policy perspective, the Digital Transportation Development Planning Outline issued by the Ministry of Transport emphasizes promoting the full-element and full-cycle digitalization of transportation infrastructure, with the goal of making China’s digital transportation industry globally competitive by 2035^[3]. The National Comprehensive Three-Dimensional Transportation Network Planning Outline clearly states that the digitalization rate of China’s transportation infrastructure should reach 90% by 2035, which has been identified as one of the nine major evaluation indicators^[4]. The Opinions on Driving the Accelerated Construction of a Strong Transportation Country through Scientific and Technological Innovation jointly issued by the Ministry of Transport and the Ministry of Science and Technology calls for accelerating independent innovation and application of building information modeling (BIM) technology, promoting the integration of new-generation information technology with transportation, and developing a new generation of intelligent transportation systems^[5]. The Notice on Supporting and Guiding the Digital Transformation and Upgrading of Highway and Waterway Transportation Infrastructure jointly issued by the Ministry of Finance and the Ministry of Transport in 2024 requires focusing on small-scale, practical, and affordable application scenarios to promote the safety enhancement of highway transportation infrastructure^[6]. A series of policies have pointed out the direction for the digital and intelligent transformation and upgrading of traffic safety management and control in China’s highway reconstruction and expansion projects.

From the perspective of technology application, the digital-intelligent technologies earlier used for traffic safety assurance in China’s highway reconstruction and expansion projects are Geographic Information System (GIS) and Building Information Model (BIM). In recent years, BIM technology has been mainly applied in reconstruction and expansion projects for three-dimensional technical disclosure, four-dimensional simulation, process simulation, and traffic diversion scheme optimization^[7], as well as BIM collaborative design and management platforms^[8]. Regarding GIS-based intelligent management and control systems, some scholars have proposed the establishment of traffic analysis platforms, intelligent driving safety guidance, and other integrated traffic safety management countermeasures for the multi-stakeholder needs during the reconstruction and expansion period^[9]. GIS-based early warning systems have also been applied to traffic safety and emergency management during reconstruction and expansion^[10]. In addition, with the increasing maturity of the theoretical framework and practical applications of smart highways^[11], the number of highway projects implementing smart upgrades using reconstruction and expansion as an opportunity is gradually increasing. For example, the reconstruction and expansion project of the Tai’an to Zaozhuang (Shandong-Jiangsu border) section of the Jingtai Expressway is the first project in China to build a smart highway based on reconstruction and expansion, forming the “reconstruction and expansion + smart highway” model^[12]. Practice in highway reconstruction and expansion projects in highly urbanized areas shows that the adoption of a digital operation management and control system for highway reconstruction and expansion can effectively improve the recognition rate and disposal efficiency of traffic safety incidents during the reconstruction and expansion period under saturated traffic volumes^[13]. Information-based temporary traffic safety facilities are an important part of management and control. Foreign studies have shown that traffic management and control systems composed of various temporary devices such as dynamic speed limit signs, portable variable message signs, and radar speed displays can significantly improve the traffic safety level of highway reconstruction and expansion projects^[14].

Overall, the phenomenon of “emphasizing hardware over software” still exists in China’s highway reconstruction and expansion projects. Large investments are made in hardware facilities, but insufficient attention is paid to digital-intelligent traffic safety management and control systems. The traffic safety management model relies too much on manual work and experience, resulting in problems such as information lag, low efficiency, and insufficient risk warning capability. From the perspective of technology transfer and application, compared with the rapid development of information and intelligent technologies, their application in traffic safety management and control of highway reconstruction and expansion is still somewhat lagging, with problems such as insufficient application of digital-intelligent technologies, large and comprehensive management and control systems, unclear functional positioning, and unclear implementation technical paths.

Therefore, this study targets the demand for digital-intelligent upgrading of highways during the 15th Five-Year Plan period, focuses on small-scale and micro-scenarios of traffic safety management and control in reconstruction and expansion projects, and based on the concepts of “reconstruction and expansion + digital-intelligent” and “operation-construction collaboration”, analyzes the traffic safety characteristics of highway reconstruction and expansion, defines the functional architecture of the management and control system, proposes an adapted digital-intelligent management and control technical path, and discusses optimization directions for current technology applications through case study analysis. The research results can provide theoretical guidance and technical support for traffic safety assurance in highway reconstruction and expansion projects, and facilitate the digital-intelligent transformation and upgrading of highway transportation infrastructure.

2. ANALYSIS OF TRAFFIC SAFETY CHARACTERISTICS OF HIGHWAY RECONSTRUCTION AND EXPANSION

To maintain the basic function of highway infrastructure and meet the basic travel needs of vehicles, the “construction while maintaining traffic flow” mode usually adopted during reconstruction and expansion is essentially a trade-off between the safety and efficiency of the highway traffic system operation under specific scenarios, aiming to achieve the overall goals of ensuring smooth traffic and safety. Under this goal orientation, clarifying the traffic safety characteristics of highway reconstruction and expansion is a prerequisite for effectively implementing traffic safety management and control. To comprehensively analyze the main problems and characteristics of traffic safety in China’s highway reconstruction and expansion, this study conducted surveys on more than 20 highway reconstruction and expansion projects in Guangdong, Shandong, Liaoning, Hubei, Xinjiang and other regions. From the engineering practice perspective, highway reconstruction and expansion sections generally suffer from complex traffic control measures, temporary changes in road alignment, and limited vehicle passage space, resulting in traffic safety characteristics different from those of normal operating sections. From the theoretical perspective, basic risk management theory reveals that traffic safety risk sources are people, objects, or events that increase the possibility of accidents or aggravate the severity of accident consequences^[15]. The road traffic system is a complex system composed of five elements: “driver, vehicle, road, environment, and management”. Each element forms its own subsystem^[16]. These subsystems act independently and constrain each other; their reliability and interactions determine the operational status and traffic safety level of this complex system.

In summary, compared with normal operating highway sections, except for meteorological environmental factors, the traffic safety issues of highway reconstruction and expansion projects have distinct characteristics. Based on field investigation and theoretical analysis, this study proposes five aspects of traffic safety characteristics of highway reconstruction and expansion: driver behavior, vehicle operation, road conditions, traffic organization, and engineering management.

1) Driver behavior characteristics: First, drivers are prone to distraction. The complex environment of the highway reconstruction and expansion work zone easily distracts drivers. Second, it easily leads to fatigued driving. Slow traffic in the work zone leads to long driving times and fatigue. Third, there are many violations. Some drivers do not comply with speed limit or lane change rules in the work zone, increasing traffic accident risks.

2) Vehicle operation characteristics: First, there are large speed differences. Speed variations in the work zone are large, easily leading to rear-end collisions. Second, following distances are relatively short. Lane reduction in the work zone leads to shortened following distances, increasing traffic accident risks. Third, the impact of large vehicles is high. Large vehicles have difficulty changing lanes in the work zone, easily causing traffic accidents.

3) Road condition characteristics: First, pavement condition deteriorates. Construction causes uneven or temporary pavement, affecting vehicle stability. Second, the visibility of signs and markings

decreases. There are many temporary signs and markings in the work zone, which may be unclear or improperly placed, easily causing driver misjudgment. Third, the risk of inadequate separation is high. Imperfect separation facilities may cause vehicles to mistakenly enter the construction area, increasing traffic safety risks.

4) Traffic organization characteristics: First, lanes are reduced. Lane reduction during reconstruction and expansion easily causes congestion and rear-end collisions. Second, traffic flow is reorganized. Frequent lane changes and merging in the work zone increase the risk of sideswipes and side collisions. Third, temporary speed limit measures bring new risks. Drivers may not adjust in time to speed limit measures in the work zone, easily leading to rear-end collisions.

5) Engineering management characteristics: First, construction vehicles frequently enter and exit the work zone, easily colliding with normal social vehicles. Second, the safety risk of workers objectively exists. Workers on the road face traffic safety risks. Third, nighttime risks are higher, further increasing traffic safety risks during reconstruction and expansion.

3. FUNCTIONAL REQUIREMENTS ANALYSIS OF THE DIGITAL-INTELLIGENT MANAGEMENT AND CONTROL SYSTEM

Based on the above characteristic analysis, this section focuses on how digital-intelligent technologies drive traffic safety management and control in highway reconstruction and expansion, analyzes typical scenarios, proposes the system functional architecture, and answers two questions: “what is” and “why” the digital-intelligent traffic safety management and control system for highway reconstruction and expansion.

3.1. Analysis of Typical Business Scenario Requirements

Based on the investigation and analysis, there are problems in the current traffic safety management and control of highway reconstruction and expansion, such as insufficient application of digital-intelligent technologies, large and comprehensive management and control systems, unclear functional positioning, and unclear implementation technical paths. From a business-driven perspective, the digital-intelligent traffic safety management and control system for highway reconstruction and expansion should be oriented towards the goal of safety and smoothness, focus on micro-scenarios and small-scale traffic safety problems, and adopt a full-process digital-intelligent technology system to provide technical support for ensuring traffic safety in highway reconstruction and expansion projects. Considering the whole-process traffic safety characteristics before, during, and after reconstruction and expansion construction, this study systematically analyzes the business requirements of traffic safety management and control in highway reconstruction and expansion projects and proposes a list of 10 scenario requirements for digital-intelligent traffic safety management and control in highway reconstruction and expansion projects, as shown in Table 1.

Table 1: List of Scenario Requirements for Traffic Safety Digitalization Management in Highway Reconstruction and Expansion Projects

No.	Typical Business Scenario	Specific Requirement Analysis
1	Safety simulation and optimization of traffic organization schemes	Use digital twin models to simulate traffic flow operation under different traffic organization schemes, evaluate the impact of schemes on indicators such as traffic safety, flow, speed, and delay, and optimize traffic organization schemes.
2	Digital design and optimization of traffic safety facilities	Use visualization technology for digital design optimization of traffic safety facilities such as signs, markings, barriers, and separation facilities, achieve visual display and collision detection of design schemes, optimize design schemes, and improve traffic safety during reconstruction and expansion.

No.	Typical Business Scenario	Specific Requirement Analysis
3	Regional traffic situation awareness	Use video surveillance, radar, geomagnetic and other devices to perceive regional traffic flow, speed, traffic safety events and other information in real time, identify abnormal situations such as traffic congestion and safety incidents based on data analysis, and release early warning information.
4	Regional traffic safety risk assessment	Use unmanned aerial vehicles (UAVs), LiDAR and other technologies to collect data on the work area and surrounding environment, identify potential safety risk points (e.g., falling objects, vehicle collisions) based on 3D models, assess the impact on traffic safety, and formulate corresponding safety protection measures.
5	Traffic safety information release and guidance	Use variable message signs, navigation apps and other channels to release traffic organization schemes, traffic control information, detour routes, etc., guide drivers to choose reasonable travel routes, and alleviate traffic safety pressure in the reconstruction and expansion area.
6	Intelligent inspection of traffic safety facilities	Use intelligent devices such as UAVs and robots to conduct regular inspections of traffic safety facilities, automatically identify facility damage, absence and other problems, improve inspection efficiency, reduce labor costs, and ensure the integrity of traffic safety facilities.
7	Traffic safety data analysis and early warning	Collect historical traffic accident data in the reconstruction and expansion area, analyze accident causes, temporal and spatial distribution patterns, identify high-risk sections and time periods based on data analysis, and formulate targeted traffic safety prevention measures.
8	Digital management of emergency plans	Based on a digital emergency plan library, achieve rapid query, retrieval, and execution of emergency plans, use digital twin technology to simulate emergency plan drills, and improve emergency response efficiency.
9	Data sharing and collaboration	Establish a unified data platform to achieve data sharing and collaborative management among multiple stakeholders during reconstruction and expansion, improve information transmission efficiency, and enhance traffic safety management.
10	Public participation and supervision	Provide functions such as risk reporting and real-time traffic conditions push, enhance public awareness, and build a co-governance and shared traffic safety environment.

3.2. Functional Architecture of the Digital-Intelligent Management and Control System

The traffic safety management and control system for highway reconstruction and expansion serves the above management and control business scenario requirements, and its system functions should be determined by the business scenarios. Based on the proposed list of scenario requirements for digital-intelligent traffic safety management and control in highway reconstruction and expansion, further research is needed to determine the system functions. This study adopts a process-oriented structured analysis method, takes the internal data of the system as the core, follows the relationship of data transmission and transformation among subsystems, and decomposes and designs the system functions from top to bottom until a physical model meeting actual needs is constructed^[17]. This method conforms to human thinking and behavior habits and is easy to implement. According to this method, the realization of each digital-intelligent management and control business scenario requires the transmission, transformation, and output of data elements among systems. The above ten digital-intelligent management and control business scenario requirements should be realized under the same management and control system framework. Following the logic of “autonomous perception → autonomous diagnosis → autonomous decision-making and control”, and considering the requirements of human-computer interaction and display, this study proposes that the digital-intelligent traffic safety management and control system for highway reconstruction and expansion should have the following five major functions. Focusing on ensuring traffic safety in highway reconstruction and expansion and serving typical business scenario requirements, the functional architecture of the digital-intelligent traffic safety management and control system for highway reconstruction and expansion projects is shown in Figure 1.

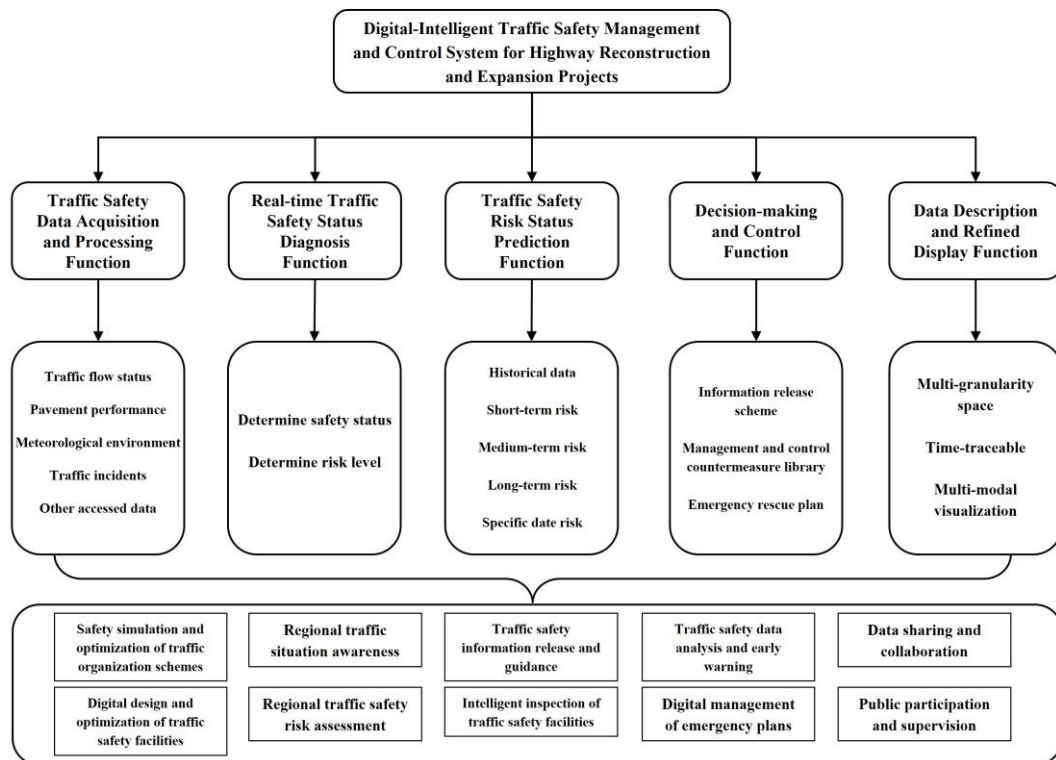


Figure 1: Functional Architecture of the Traffic Safety Digitalization Management System for Highway Reconstruction and Expansion Projects

1) Data acquisition and processing function for traffic safety in reconstruction and expansion projects. This function is the “cornerstone” of the entire management and control system. Data perception is the prerequisite for all digital-intelligent management and control work. For the whole-process, all-element traffic safety risk sources during highway reconstruction and expansion, the management and control system should be able to obtain multi-source data in real time, including traffic flow status, pavement performance, meteorological environment, and traffic incidents in the reconstruction and expansion section, and perform efficient fusion and preprocessing. Therefore, this is the basic function that the system should possess to achieve the digital-intelligent management and control of the ten business scenarios mentioned above.

2) Real-time traffic safety status diagnosis function for reconstruction and expansion projects. Based on the processed fused data, this function performs real-time “health checks” on the current reconstruction and expansion traffic system, accurately identifying abnormal states and safety risks. Using the collected information and intelligent algorithms, the system should be able to diagnose the real-time traffic safety status of highway reconstruction and expansion sections, determine the traffic safety level, and provide basic information for traffic safety risk early warning and management and control decisions. This function provides algorithm models and traffic safety status results for realizing business scenario requirements such as “safety simulation and optimization of traffic organization schemes”, “digital design and optimization of traffic safety facilities”, “regional traffic situation awareness”, and “regional traffic safety risk assessment”.

3) Traffic safety risk status prediction function for reconstruction and expansion projects. This function extends from “current status diagnosis” to “future prediction”, using historical and real-time data to predict short-term safety situations, achieving a shift from “passive response” to “active prevention and control”. To better manage traffic safety risks in the reconstruction and expansion section over a future period, the system should be able to predict the traffic safety risk status of the section in the near future. Business scenarios such as “traffic safety information release and guidance” and “traffic safety data analysis and early warning” require the prediction results provided by this system function to effectively

guide road users in the road network area where the reconstruction and expansion project is located, and also provide a basis for management departments to carry out risk assessment and prevention.

4) Decision-making and control function. This function is the “command center” of the system, automatically or semi-automatically generating optimal management and control strategies based on diagnosis and prediction results, and linking with execution devices for precise control. Based on autonomous perception and diagnosis, the system should be able to automatically provide reasonable decision-making suggestions according to real-time traffic safety risk diagnosis and prediction results and a preset management and control countermeasure library, including real-time traffic information release schemes, flow restriction, lane restriction, speed limit measures, emergency rescue plans, etc., and then achieve risk control through external hardware facilities matched with the digital system. Business scenarios such as “traffic safety information release and guidance”, “intelligent inspection of traffic safety facilities”, and “digital management of emergency plans” all require the system to have autonomous decision-making and control capabilities.

5) Data description and refined display function. This function is the “display window” of the system, presenting complex internal data and decision-making processes in an intuitive and visual way to serve different user roles. To achieve good human-computer interaction and serve road users and management departments for business scenarios such as “data sharing and collaboration” and “public participation and supervision”, the system should be able to retrieve and query real-time and historical data related to traffic safety in highway reconstruction and expansion projects. At the same time, the digital-intelligent traffic safety management and control system should also have good visualization effects and refined display functions at different levels. That is, the system should have functional features such as multi-granularity space, time-traceability, and multi-modal visualization.

4. TECHNICAL PATH FOR IMPLEMENTING THE DIGITAL-INTELLIGENT MANAGEMENT AND CONTROL SYSTEM

After clarifying “what is” and “why” the digital-intelligent traffic safety management and control system for highway reconstruction and expansion, further analysis is needed on the digital-intelligent technologies adapted to business scenarios and management and control functions, as well as their implementation path, to answer the question of “how to do it”.

4.1. Key Digital-Intelligent Technology System Adapted to Scenarios and Functions

The realization of the functions of the digital-intelligent traffic safety management and control system for highway reconstruction and expansion projects requires the support of digital, information, and intelligent technologies. This subsection analyzes the key technologies involved. Based on a full investigation of the development status of digital, artificial intelligence, large model and other technologies at home and abroad, and following the principle of “currently available and moderately forward-looking”, matching the five major system functions proposed in Section 2, this study forms a key digital-intelligent technology system adapted to the business scenarios and management and control functions of highway reconstruction and expansion projects. Among them, the real-time traffic safety status diagnosis function and the traffic safety risk prediction function are analyzed together because the required digital-intelligent technologies are similar. As shown in Table 2.

Table 2: Key Digitalization Technology System for Traffic Safety Control Scenarios and Function Adaptation in Highway Reconstruction and Expansion

System Function	Key Digital-Intelligent Technologies
Data acquisition and processing	<ul style="list-style-type: none"> • LiDAR, UAV aerial survey (acquiring high-precision geographic information) • Millimeter-wave radar, AI cameras (traffic flow monitoring) • On-board OBD terminals (vehicle status monitoring) • Big data platform: Hadoop/Spark architecture for storing multi-source heterogeneous data • AIoT (intelligent Internet of Things): comprehensive perception of people, vehicles, roads,

System Function	Key Digital-Intelligent Technologies
	and environment through sensor networks <ul style="list-style-type: none"> • Smart wearable devices (personnel positioning, vital signs monitoring) • Distributed database technology
Real-time traffic safety status diagnosis; Traffic safety risk prediction	<ul style="list-style-type: none"> • Edge computing: real-time processing of sensor data, reducing cloud dependency • AI algorithm models: computer vision, deep learning, reinforcement learning, etc. • Digital twin technology: integrating BIM+GIS+IoT to form a closed loop of “physical area + virtual model + real-time data”, achieving virtual-real mapping of traffic safety status • Traffic simulation and deduction technology: Vissim, TransCAD and other tools to simulate traffic flow, evaluate traffic safety status and risk levels
Decision-making and control function	<ul style="list-style-type: none"> • Intelligent decision support technology: generating suggestions for optimizing traffic safety measures, emergency rescue plans, etc. based on data analysis • Traffic large model technology • BIM+GIS fusion technology: achieving precise matching of traffic safety facility status, control schemes, and geographic space • Intelligent roadside equipment: variable message signs, dynamic speed limit signs, etc.
Data description and refined display function	<ul style="list-style-type: none"> • Web-side: visualization technology for management departments, providing multi-modal display effects • Mobile-side: APPs, public mini-programs • Network security technology: ensuring the security and credibility of cross-departmental data sharing

4.2. Technical Path for Digital-Intelligent Traffic Safety Management and Control

To further answer the question of “how to do it”, based on the key digital-intelligent technology system adapted to business scenarios and management and control functions proposed in the previous subsection, the logical relationship between them needs to be established and the implementation technical path clarified. To realize autonomous perception, autonomous diagnosis, autonomous decision-making and control for traffic safety in highway reconstruction and expansion projects, this study proposes a technical path for digital-intelligent traffic safety management and control in highway reconstruction and expansion, as shown in Figure 2.

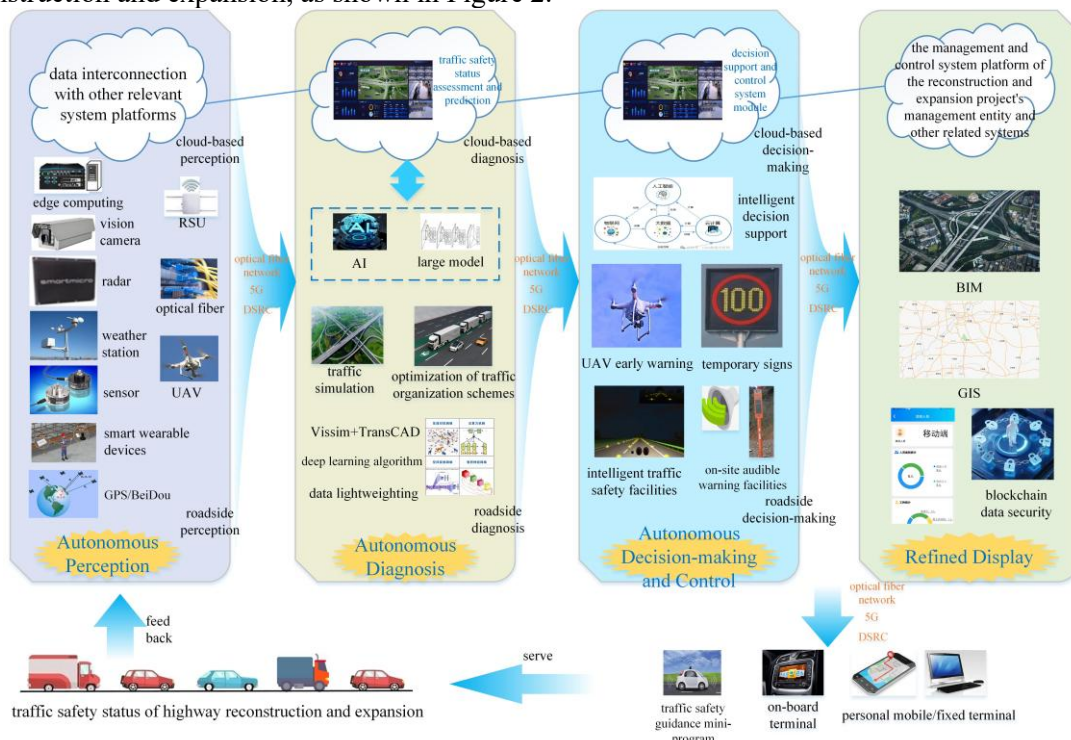


Figure 2: Technical Path for Intelligent and Digitalized Traffic Safety Management in Highway Reconstruction and Expansion

The technical path closely revolves around the core goal of traffic safety in highway reconstruction and expansion projects. A high-precision perception network comprehensively captures risk elements of “people, vehicles, roads, and environment”. Real-time diagnosis and risk prediction functions achieve extremely early detection and warning of traffic anomalies and accident hazards. Relying on intelligent decision-making and control functions, the optimal traffic organization and guidance schemes are quickly generated and executed, thereby resolving risks before they evolve into accidents. Finally, through integrated data display, managers and users are provided with a clear and transparent perception of the safety situation. Following this entire technical path, a closed-loop digital-intelligent traffic safety prevention and control system characterized by “sensible, knowable, measurable, and controllable” risks is formed, with good data description and display effects, which can minimize traffic safety accidents during highway reconstruction and expansion, assist in the digital-intelligent transformation and upgrading of highway transportation infrastructure, and build a safe and reliable travel corridor for the public.

5. CASE STUDY

5.1. Typical Cases of Highway Reconstruction and Expansion Projects in China

Case study analysis is a logical method to obtain general understanding through in-depth study of representative cases, also known as case analysis or typical analysis^[18]. It is a cyclic process where theory guides practice and practice enhances understanding. To analyze the current application status of digital-intelligent traffic safety management and control systems in highway reconstruction and expansion and identify improvement directions, this study reviews ten typical cases of highway reconstruction and expansion projects implemented in China in recent years based on public information. The details of the project characteristics are shown in Table 3.

Table 3: Overview of Typical Cases of Highway Reconstruction and Expansion Projects

No.	Project Name	Province	Completion Year	Reconstruction & Expansion Year
1	Jinan-Qingdao Highway Reconstruction and Expansion Project	Shandong	1993	2016-2019
2	Tai'an to Zaozhuang (Shandong-Jiangsu Border) Section of Jingtai Expressway Reconstruction and Expansion Project	Shandong	2002	2018-2021
3	Jingha Expressway Reconstruction and Expansion Project	Liaoning	1999	2022-2025
4	Lidong Reconstruction and Expansion Project of Shanghai-Kunming Expressway	Jiangxi	2002	2022-2025
5	Kaiyang Expressway Reconstruction and Expansion Project	Guangdong	2003	2018-2020
6	Shenzhen-Shanwei West Expressway Reconstruction and Expansion Project	Guangdong	1996	2020-2024
7	Huocun to Longshan Section of Shenyang-Haikou National Expressway Reconstruction and Expansion Project	Guangdong	2001	2023-2028
8	Guangzhou Airport Expressway Reconstruction and Expansion Project	Guangdong	2002	2020-2023
9	Shenzhen Jihe Expressway Reconstruction and Expansion Project	Guangdong	1999	2025-
10	G15 Jialiu Section Widening and Reconstruction Project	Shanghai	1990s	2020-2023

5.2. Analysis of Application Effectiveness of Digital-Intelligent Management and Control Systems

The functions of the management and control system in the engineering cases reflect, on one hand, the understanding and positioning of traffic safety management and control by the project management parties of highway reconstruction and expansion projects, and on the other hand, the application level of digital-intelligent technologies and the clarity and feasibility of the adopted technical paths. To further quantitatively evaluate the application status of digital-intelligent systems in traffic safety management and control of highway reconstruction and expansion projects in China at the current stage, this study proposes the evaluation indicator of system functional completeness, which is calculated as the ratio (%) of the number of functions possessed by the management and control system in actual projects to the number of functions that the system framework proposed in this study should possess (5 functions). Based on this method, the quantitative evaluation results of the application status and functional characteristics of digital-intelligent management and control systems in the above ten typical engineering cases are shown in Table 4.

Table 4: Quantitative evaluation results of the application status and functional characteristics of digital-intelligent management and control systems in typical engineering cases

Case No.	Digital management and control system applied?	Functional characteristics					Functional completeness (%)
		Data perception and processing	Traffic safety status diagnosis	Traffic safety risk prediction	Decision-making and control	Data description and refined display	
1	Yes	✓	✓		✓		60%
2	Yes	✓	✓		✓	✓	80%
3	Yes	✓	✓	✓	✓	✓	100%
4	Yes	✓	✓	✓	✓	✓	100%
5	Yes	✓			✓	✓	60%
6	Yes	✓	✓	✓	✓	✓	100%
7	Yes	✓			✓	✓	60%
8	Yes	✓	✓		✓		60%
9	Yes	✓	✓	✓	✓	✓	100%
10	Yes	✓	✓		✓	✓	80%
Average							80%

From Table 4, it can be seen that the current functional completeness of digital-intelligent management and control systems in China's highway reconstruction and expansion projects is about 80%. Among them, data perception and processing, decision support and control are basic functions commonly possessed by the engineering cases, but there are differences in the degree of decision support and effectiveness. Another 80% of the systems have data description and refined display functions, which is mainly related to the development time of BIM and 3D GIS technologies. The most lacking aspects are traffic safety status diagnosis and traffic safety risk prediction, which also reflects the current problems of large and comprehensive reconstruction and expansion management and control systems, insufficient precision in traffic safety management and control, and unclear system functional positioning. These should be the directions for focused improvement in future development.

6. CONCLUSION

This study, based on the development trends of the digital and intelligent era, oriented to the requirements of "digital-intelligent upgrading" of China's highways during the 15th Five-Year Plan period, focuses on the business needs of traffic safety management and control in highway

reconstruction and expansion projects, adopts process-oriented structured analysis and case study methods based on risk management and systems engineering theory, and addresses the problems of insufficient application of digital-intelligent technologies, unclear system functional positioning, and unclear technical paths in traffic safety management and control of highway reconstruction and expansion. The main research conclusions are as follows:

- 1) Compared with normal operating highway sections, except for meteorological environmental factors, highway reconstruction and expansion projects have significantly different traffic safety characteristics in five aspects: driver behavior, vehicle operation, road conditions, traffic organization, and engineering management.
- 2) Based on typical business scenario requirements, the digital-intelligent traffic safety management and control system for highway reconstruction and expansion should have five major functions: data acquisition and processing, real-time traffic safety status diagnosis, traffic safety risk prediction, decision-making and control, and data description and refined display.
- 3) Following the logic of “autonomous perception → autonomous diagnosis → autonomous decision-making and control” and based on the adaptation requirements of business scenarios and management and control functions, a key technology framework and its implementation path for digital-intelligent traffic safety management and control in highway reconstruction and expansion projects are constructed.
- 4) At present, the overall functional completeness of digital-intelligent management and control systems in China’s highway reconstruction and expansion projects is 80%. The traffic safety status diagnosis and traffic safety risk prediction functions should be the directions for focused optimization and improvement in the future development of traffic safety management and control systems for highway reconstruction and expansion.

The research results improve the digital-intelligent traffic safety management and control technology system for highway reconstruction and expansion projects, provide theoretical guidance and technical support for comprehensively adopting digital-intelligent technologies to solve the prominent traffic safety problems under the “construction while maintaining traffic flow” mode, and facilitate the digital-intelligent transformation and upgrading of China’s highway transportation infrastructure. At the same time, with the rapid development of information technologies such as big data and artificial intelligence in the current and future periods, the system framework and technical path of the digital-intelligent traffic safety management and control system for highway reconstruction and expansion should be continuously optimized and improved. Next, we will fully combine the engineering practice of highway reconstruction and expansion projects in various regions of the country to continuously carry out demonstration applications and iterative optimization of the digital-intelligent management and control system proposed in this study.

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