Citation: LI Yan, WANG Jifeng, CHEN Sha, WANG Yuxuan, MAO Haixiao. Design and Implementation of the National Urban Road Network Reliability Monitoring Platform[J], Urban Transport of China, 2023, 21 (6): 45–52.

Design and Implementation of the National Urban Road Network Reliability Monitoring Platform

LI Yan, WANG Jifeng, CHEN Sha, WANG Yuxuan, MAO Haixiao

China Academy of Urban Planning & Design, Beijing 100037, China

Abstract: In order to conduct thorough and comprehensive assessment and monitoring of urban road networks under real-world scenarios, the authors, for the first time, establish a platform for two-tiered "national–urban" collaborative monitoring on road network reliability using transportation big data related to road networks and traffic conditions and addressing the management needs at both national and city levels. This platform is developed based on three major categories, namely structural reliability, operational reliability, and capacity reliability, with 11 indicators. Five functional modules are developed, including reliability indicator computation, results visualization, comprehensive assessment diagnosis, national monitoring, and automatic report generation. This platform involves breakthroughs in indicators computation based on massive data and applies these indicators to the reliability assessment of real large-scale road networks, reducing the computational complexity and significantly enhancing the operational efficiency. Taking the Shibei District in Qingdao as an example, the paper presents the evaluation and diagnosis of road network reliability, identifying unreliable zones, corridors, and nodes within the road network. This analysis provides support for subsequent improvements in urban road network reliability. **DOI:** 10.13813/j.cn11-5141/u.2023.0604-en

Keywords: urban road network; road network reliability; indicator system; monitoring platform; functional modules; Qingdao

0 Introduction

Frequent traffic accidents, temporary road maintenance and traffic control, sudden natural disasters (such as earthquakes, floods, and severe weather), and other unexpected internal and external disruptive factors pose a significant threat to the reliable operation of urban road networks. They also have adverse effects on urban transportation functions and urban development. Currently, the country is vigorously building resilient cities with the aim of enhancing the city's ability to respond rapidly, maintain basic system operation, and quickly recover and achieve a safer state after facing emergencies such as economic crises, public health emergencies, and terrorist attacks. Monitoring on road network reliability is the basis for recording the status of urban road traffic systems, accurately identifying unreliable nodes and segments, and promptly taking preventive and recovery measures. Therefore, monitoring urban road network reliability and designing a road network reliability monitoring platform at a macro level are important guarantees for realizing resilient city construction.

The existing research on road network reliability has achieved many results, and there are many reliability measurement methods. Since the concept of connectivity reliability was proposed by H. Mine et al. [1] in 1982, many scholars have made improvements and conducted further research based on this foundation [2–4]. The indicators of road network reliability mainly include connectivity (road network structure) reliability, travel time reliability, and capacity reliability [5]. Hu et al. [6] fitted the urban road network as a complex network and used complex network metrics such as centrality and information degree to evaluate the structural reliability of the road network. Xu [5] established a method for measuring the operating status reliability of road network based on the road segment–road network structure. The road segment reliability was measured by selecting the 95% quantile travel time, and the road network reliability was determined by weighting the segment capacity allowance, road segment grade, and road segment connectivity. Additionally, the reliability of the Lianyungang road network was simulated using VISSIM. Tang et al. [7] used road network recovery reliability as an assessment indicator for the operating status of the road network, evaluating the ability of road segments and road networks to restore normal functions within the expected time after sudden events. Cheng et al. [8] used taxi data to calculate three factors: road network connectivity, travel time, and traffic volume, to evaluate road network reliability. Fang et al. [9] established a double-layer planning model of road network reliability based on constraints for road service level and solved it using sensitivity analysis. The results indicated that the proposed model could be used to evaluate the road network performance under different road service levels.

Received: 2023-04-30

Cheng et al. [10] evaluated travel time reliability using two indicators: 90% quantile travel time and travel time fluctuation, and designed a dynamic traffic system for simulation and evaluation on the reliability of urban road network. Although Chinese scholars have conducted research on assessment indicators of road network reliability and designed simulation systems based on various data and methods, there are still problems in reliability assessment, such as singular use of indicators, limited application scope of road networks, simplification of data usage, and deviation of simulation predictions, making it challenging to apply them to the ever-changing road networks in real-world situations and to monitor road networks throughout entire cities or country.

Relying on the project funded by the National Key Research and Development Program "Key Technologies for Road Space Organization Based on High-Intensity Urban Travel", in this study we proposed a technology system for assessment and monitoring of road network centered around reliability. Addressing diverse needs at both national and urban levels, we established a national–urban road network reliability monitoring platform (hereinafter referred to as the "platform"). Starting from the demand for monitoring of urban road network reliability, the platform supports the collection, storage, interaction, and computation of multidimensional reliability indicators for multi-source, real-time, and massive road network data. Based on the computation results of these indicators, it achieves dynamic assessment on the reliability of urban road network, thereby serving relevant national regulatory authorities and urban road planning and construction management authorities to enhance the efficiency of urban road network security.

1 Platform architecture design

1.1 Application scenarios

The platform architecture design is based on two main application scenarios: national monitoring and urban assessment.

1) National monitoring focuses on addressing the evaluation and lateral comparison of the reliability, operational reliability, and capacity reliability of the road network structures in major cities. It guides the direction of road network construction and risk prevention in various cities. Its main objectives are sustainability, comparability, and scalability. Sustainability refers to regular updating of indicators on a daily, weekly, monthly, and yearly basis; comparability ensures standardization of the data processing process and the comparability of indicators; scalability requires ensuring the replicability of indicator algorithms.

2) For road networks in central urban areas, urban assessment focuses on deeply exploring unreliable nodes, road segments, corridors, and zones to directly guide planning and construction of urban road network. Its main objectives are guidance, comprehensiveness, and practicality. Guidance means being demand-oriented, reflecting and addressing practical issues. Comprehensiveness refers to selecting indicators from multiple dimensions to ensure the scientific integrity of the assessment indicator system. Practicality means that the indicator algorithms developed by the platform should be easy to compute.

1.2 Overall architecture

The overall architecture of the platform consists of an infrastructure service layer, data service layer, support layer, and application layer (see Fig. 1). 1) The infrastructure service layer consists of platform infrastructure equipment, computing resources, storage resources, network resources, data storage, data processing, security resources, and other hardware and software environments, which support the implementation of various module functions of the platform. 2) The data service layer mainly implements data aggregation, access, sharing, and publication services. It builds a standard database for reliability calculation based on a reliability indicator library and ensures efficient indicator calculation and data services through distributed computing, distributed retrieval, real-time computing, and database SQL computing. 3) The support layer mainly consists of general services, computing services, visualization services, evaluation services, and report generation services. 4) The application layer is an important application scenario of the road network reliability monitoring platform, including national monitoring and urban assessment. The platform development process is conducted under the constraints of relevant security management systems, operation and maintenance management norms, and development standard specifications.

1.3 Functional module design

To serve planning, construction, management of urban road network, and relevant national regulatory authorities, the platform is designed with five functional modules: reliability indicator computation, result visualization, comprehensive assessment and diagnosis, national monitoring, and automatic report generation, forming 13 business lines. Each business line can be further divided into several sub-business lines based on reliability indicators. The application architecture of the platform is shown in Fig. 2.

Based on the analysis and research of the macroscopic characteristics of urban road networks, 11 indicators in three categories were selected to construct a library for assessment and computation of reliability indicators for road networks. Structural reliability indicators include road segment importance, structural reliability of road segment, structural reliability of road network, and failure impact scope of road segment. Operational reliability indicators include time reliability of road segment, path time reliability, commute time reliability, and time reliability of road network. Capacity reliability indicators include capacity reliability of road networks and grids, and road network supply–demand balance reliability. Among them, structural reliability of road network, commute time reliability, time reliability of road network, and capacity reliability of road network serve as common monitoring indicators for major cities nationwide.

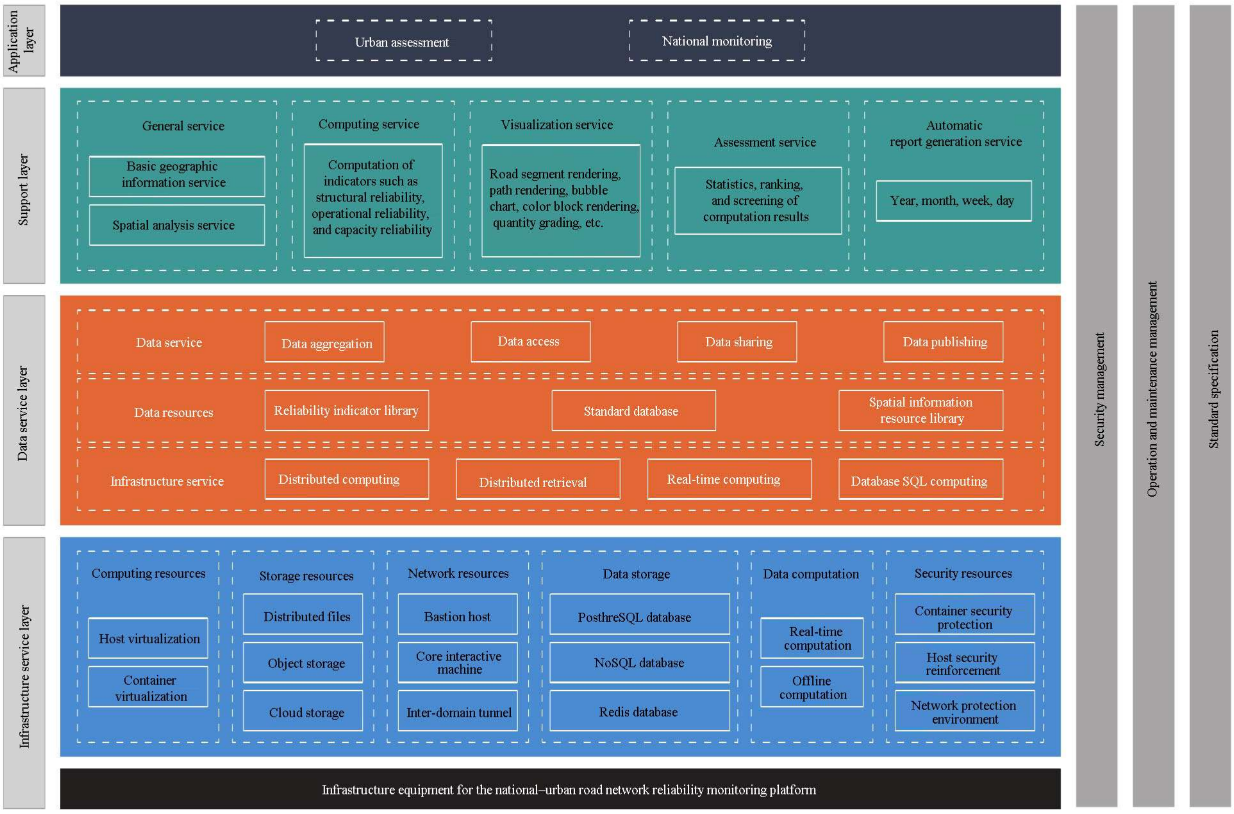


Fig. 1 Overall architecture of the national–urban road network reliability monitoring platform

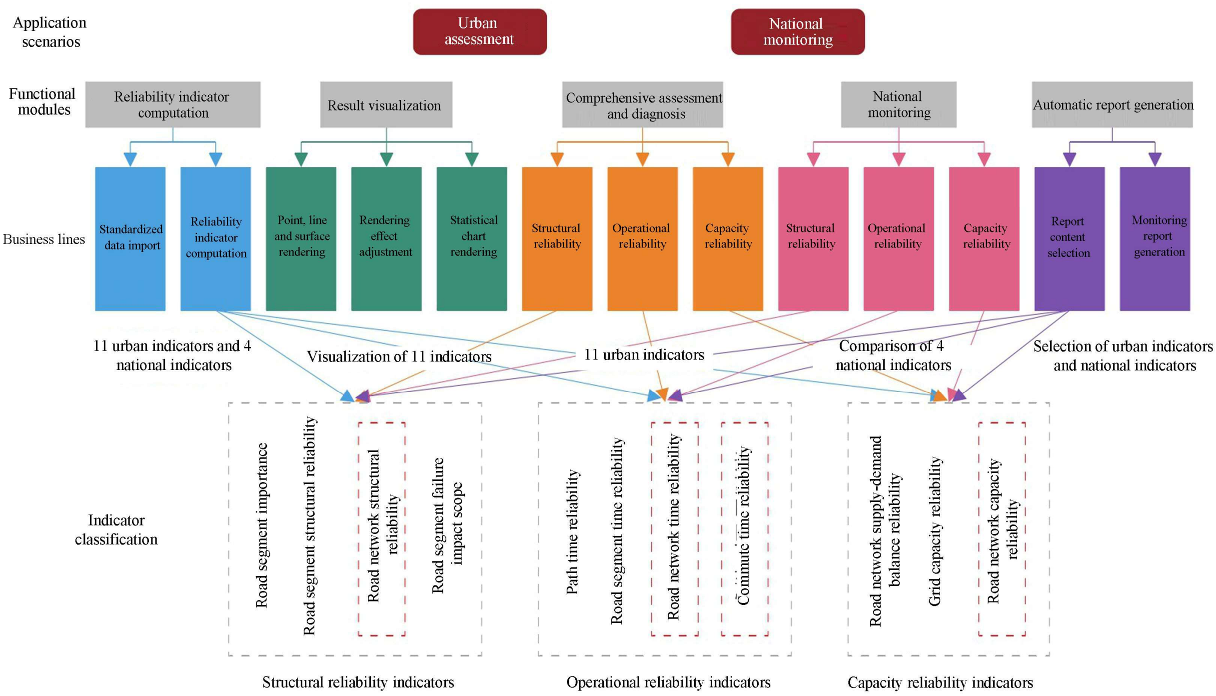


Fig. 2 Application architecture of the national–urban road network reliability monitoring platform

The functional module for reliability indicator computation calculates the reliability of municipal-level and district-level road networks. The functional module for result visualization categorizes and displays the computation results. The functional module for comprehensive assessment and diagnosis evaluates the computation results through scoring. The national monitoring functional module conducts horizontal comparisons and monitors the results of reliability indicators for national-level road networks. The functional module for automatic report generation generates customized report combinations based on computation results of different indicators.

2 Platform development and implementation

2.1 Development foundation

The platform is developed using the Java language, within the JDK 1.8 development environment, and based on IntelliJ IDEA 2018.3.2. The graphical user interface is built using Vue 2.0, while the database service is developed using PostgreSQL, and ECharts is employed for graphical rendering, achieving the overall functionality of the platform modules.

2.2 Key technologies

2.2.1 Database construction

Database construction is a key component of the platform, within which the indicator library serves as the prerequisite for data. It is necessary to clearly define the data format and key fields required for input based on the indicators to be evaluated at the national and urban levels. The indicator library for the national–urban road network reliability monitoring platform is shown in Table 1. Based on the definitions and computation methods of the above indicators, the core data required for indicator computation is specified (as shown in Fig. 3).

Table 1 Indicator library of the national–urban road network reliability monitoring platform

Indicator category	Specific indicator	Indicator description and computation method
Structural reliability indicators	Road segment importance	The shortest path allocation on the road network without traffic loading is performed. Thenumber of OD pairs passing through a certain road segment is recorded, and used as a road segment importance indicator. The road segments with number of OD pairs in top 20% are recorded as critical segments, with each 20% forming one level, for a total of 5 levels.
	Structural reliability of road segment	The shortest path allocation on the road network without traffic loading is performed, and a road segment is randomly selected to fail (where the travel time of the segment tends to infinity). The structural reliability of road segment is determined by comparing the impact on the road network before and after the segment failure.
	Structural reliability of road network	The road network structural reliability is obtained by comparing the impact on the road network after the destruction of critical road segments (the increment of the overall travel time of the road network).
	Impact scope of road segment failure	The shortest path allocation on the road network without traffic loading is performed, and the total area of the grids containing OD passing through a particular road segment is chosen as the impact scope of road segment failure.
Operational reliability indicators	Time reliability of road segment	The historical travel time of road segments is sorted in ascending order at an interval of 10 min. The difference between the 95% quantile and the 50% quantile of the historical travel time is calculated, divided by the 50% quantile, to obtain the time reliability of road segment.
	Path time reliability	The shortest path is found based on the OD pair of origin and destination, travel time, and 50% quantile of the historical travel time for the road segment. The congested road segments is selected along the path. The buffer time for congested road segments is calculated by subtracting the 50% quantile from the 95% quantile of the historical travel time for the segments. Then, the sum of the buffer time is divided by the sum of the 50% quantiles of historical travel time for all road segments in the path to obtain the path time reliability.
	Time reliability of road network	The 50% quantile is subtracted from the 95% quantile of historical travel time of all congested road sections within a specific period (such as peak hours) to obtain the buffer time of the congested road segments. Then, the sum of the buffer time is divided by the sum of the 50% quantiles of historical travel times for all network segments to obtain the time reliability of road network.
	Commute time reliability	It is derived from the aggregation of path time reliability. OD pairs are selected for commuting purposes, and OD pairs are chosenwithin a certain commuting distance range at a specific time. Their path time reliability is chosen, and a weighted average is performed according to the shortest path time to obtain commute time reliability.
Capacity reliability indicators	Supply–demand balance reliability of road network	Grid division is conducted at a spatial scale of 500 m. Based on all-mode travel data, the traffic generation and attraction volume within each grid are calculated and converted into total person trips as demand coefficients, which are then categorized into five levels. The supply levels of each grid are calculated based on the number of public bus and tram stations, urban rail transit stations, and road network density. These are also converted into total person trips and categorized into five levels, consistent with the grading criteria for demand coefficients. The difference between the levels of demand and supply yields the supply–demand balance reliability of road network.
	Grid capacity reliability	Based on traffic volume data such as all-mode OD data and tollgate data, the traffic volume of the road segment is obtained. Grid division is conducted at a spatial scale of 500 m. The traffic volume of roads intersecting with grid boundaries during peak hours is calculated. The ratio of the total traffic volume of intersecting roads to the sum of their theoretical capacity is then calculated to determine the grid capacity reliability.
	Reliability of road network capacity	The percentage of grids with a grid capacity reliability of 0.7 or higher among the total number of grids is calculated to obtain the reliability of road network capacity.

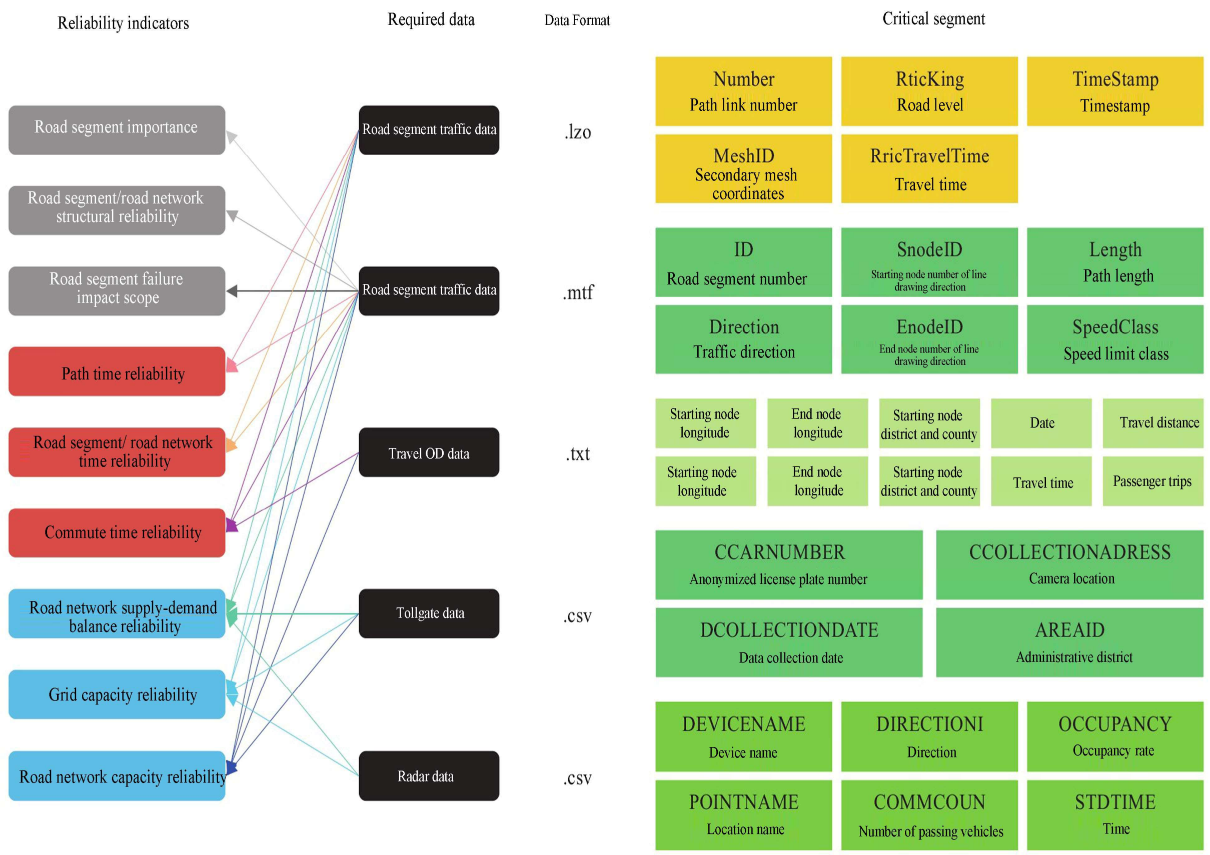


Fig. 3 Core data required for indicator calculation

2.2.2 Real-time data interchange and transmission

The platform involves real-time transmission and processing scenarios of big data, utilizing stream data transmission in distributed data storage systems. In stream data processing, monitoring and collecting data continuously arrive, and the system promptly handles newly arrived data, continuously providing feedback to system terminals and subsystems. Ultimately, it achieves the capability to provide platform application services, including spatial analysis service, vector map service, real-time data service, historical data service, and other data service contents. Based on the aforementioned service capabilities, it ultimately provides corresponding data analysis for monitoring results.

2.2.3 Data service function

The platform data storage and data provision services to various interfaces primarily rely on data access, data storage, infrastructure services, and top-level references to provide data services to various businesses.

1) Data access: The platform provides vector data of urban road networks nationwide and creates dynamic traffic data interfaces based on floating vehicle data, such as vehicles with passengers and dangerous goods, and taxis.

2) Data storage: Spatial data such as urban road networks and road conditions received through data interfaces are processed by the Elastic Search library to generate indices and log data of raw data, which are then stored in a vector database using the Ceph library. Dynamic traffic data are processed through Kafka to provide dynamic traffic services, ultimately generating business metadata (Postgres) used by the platform. Business metadata enable functions such as data statistics, access control, and data read and write operations.

3) Infrastructure services: The Pipeline K8S cluster is utilized to process traffic data, and this module's work is completed based on the task executor and data processing management. The task executor primarily implements executor tasks such as services and registration threads, while the scheduler primarily implements tasks such as scheduling services and registrars. Data processing management primarily handles the pipeline, achieving the processing of data such as urban road networks and road segment conditions.

4) Top-level references: It includes three parts: data interface API, data set SDK, and data processing SDK. The data set SDK mainly handles tasks such as creating data sets, deleting data sets, uploading data, downloading data, and archiving data. The data processing SDK mainly deals with tasks such as creating pipeline templates, creating pipelines, configuring pipeline parameters, executing pipelines, checking pipeline status, and viewing pipeline execution logs.

2.3 Function implementation

2.3.1 Reliability indicator computation and result visualization modules

The platform provides an explanation of the reliability indicators for urban road networks, where users can view the definitions, computation methods, grading rules, data input, data output, and computation flowcharts for three categories of indicators: structural reliability, operational reliability, and capacity reliability.

The platform provides computation functions for various indicators. Based on the applicability of different indicators, the platform calculates some indicators as comprehensive assessment indicators at the road network level, while others are provided as assessment tools for personalized assessment services. After selecting the desired city, computation time, and indicators, the platform can use backend data to calculate the indicators.

1) Structural reliability

The assessment of road segment importance (assessment tool) includes 6 functions: selecting indicator analysis scope (by administrative division), setting layer styles (choosing display layers; setting layer colors, thickness, transparency, etc.), selecting to view the attributes of a certain road segment (click to view the ID of a certain road segment, the number of origin–destination (OD) pairs passing through it, the area it belongs to, importance level, etc.), analyzing the proportions of different levels of road segment importance within the analysis scope, key segment lists, and exporting results.

It requires selecting the city, time periods, and indicators for computation to calculate the structural reliability of urban-level road networks. Specifically, it includes 10 functions: selecting the indicator analysis scope (by administrative division), selecting the influencing mode, filtering and displaying the road network, setting layer styles, selecting to view the attributes of a certain road segment (clicking to view the ID of a certain road segment, the area it belongs to, reliability indicators), displaying the basic parameters of the road network (density of each road level, and graded road network structural reliability), statistical analysis of structural reliability results, displaying structural reliability rankings, reliability results, and publishing computation results.

The assessment of the impact scope of road segment failure (assessment tool) includes 5 functions: selecting the indicator analysis scope, selecting the computation method (choosing potential OD or using real OD in the indicator calculation method), selecting the road segment (choosing a specific road segment and viewing the impact scope after its failure on the map), comparing the specific values of the failure scope of the selected road segment, and viewing the attribute information of the selected road segments.

2) Operational reliability

Path time reliability (assessment tool) includes 3 functions: selecting the start and end points for path search, recommending paths with reliable travel time (routes with smaller travel buffer time), and displaying alternate paths.

Time reliability of road segment and road network include 6 functions: selecting the indicator analysis scope, selecting the analysis period, setting layer styles (optional layers include segment time reliability, administrative boundaries, etc.), viewing road segment details, list for time reliability of road segment, and time reliability of road network during peak hours.

Commute time reliability includes 8 functions: selecting the indicator analysis scope (by administrative division), commuting distance, travel date, travel period, selecting OD display, setting OD line styles (choosing display line colors, thickness, transparency, etc.), and setting styles for generating attraction points for travel (choosing display surface colors, size, transparency, etc.) and lists for assessment of commute time reliability.

3) Capacity reliability

Grid capacity reliability and capacity reliability of road network include 3 functions: selecting analysis scope, selecting layer styles, and data lists for each zone.

The supply–demand balance reliability of road network includes 4 functions: selecting the indicator analysis scope, selecting analysis type, setting layer styles, and partitioning supply–demand data lists.

2.3.2 Comprehensive assessment and diagnosis module

Based on the results of reliability indicator computation, comprehensive assessment on the reliability of urban road network is conducted. Specifically, it includes 6 functions: selecting the city for assessment, choosing assessment indicators and assessment time, selecting comparison cities, displaying selected indicator values, presenting selected indicator scores, and comparing indicator values for selected cities. The interface of the comprehensive assessment and diagnostic module for road network reliability is shown in Fig. 4.

Fig. 4 Interface of the comprehensive assessment and diagnosis module for road network reliability

2.3.3 National monitoring module

36 major cities nationwide are selected as the research subjects, including 4 municipalities directly under the central government, 27 provincial capital cities, and 5 separately planned cities. For each city, the central urban area is chosen as the scope for assessment of road network reliability, which refers to the central urban area range explicitly defined in the current overall urban planning of each city. To meet national monitoring requirements, 4 indicators are selected for comparative monitoring in each city. For structural reliability indicators, road network structural reliability is chosen. For operational reliability indicators, road network time reliability (during peak hours) and long-distance (greater than 10 km) commute time reliability are selected. For capacity reliability indicators, reliability for road network capacity is chosen. The national monitoring module includes 4 functions, namely, selecting city classification, selecting indicators and initiating computations, displaying the results of reliability rankings for major cities, and exporting monitoring results (shown in Fig. 5).

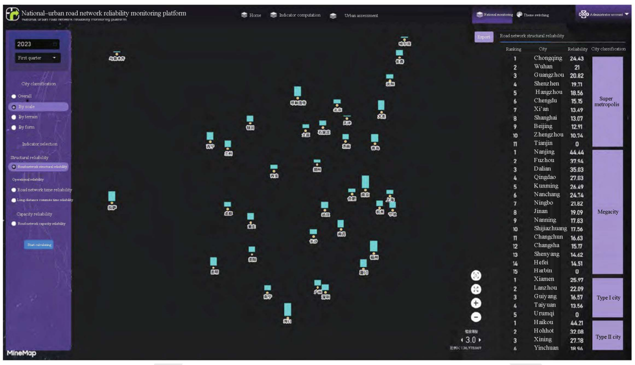


Fig. 5 Interface of the national monitoring module

2.3.4 Automatic report generation module

The module of automatic report generation consists of two parts. The first part is the calculation function module for reliability index, where the platform generates reports containing various reliability results upon completing the index calculation process. These reports are then disseminated through specific channels, including email, personal WeChat, and WeChat public accounts. Prior to dissemination, a preview of the content to be published is available (see Fig. 6).

The second part is the national monitoring module, which automatically generates reliability monitoring reports for the central urban road networks of major cities nationwide after reliability index calculations and rankings. During the report generation process, customization options are available to select the included indicators, city classifications, and assessment results for typical cities (shown in Fig. 7).

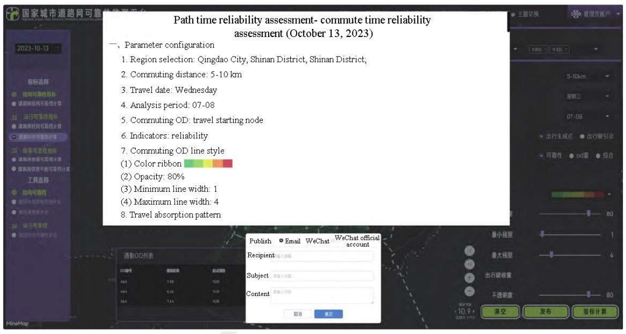


Fig. 6 Automatic report generation and publication functions in the indicator calculation module

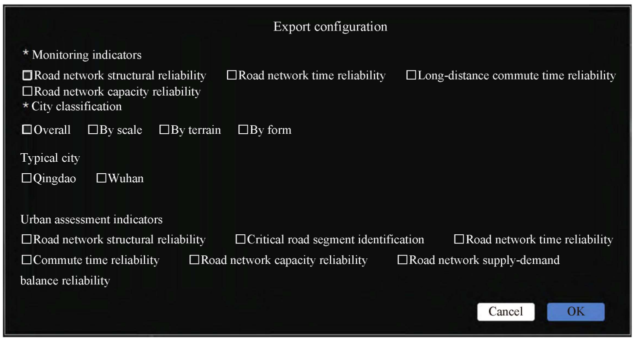


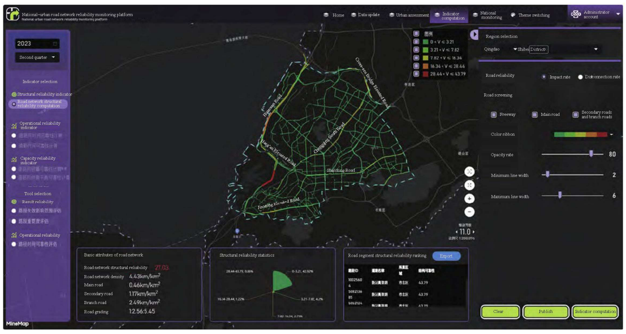
Fig. 7 Interface of automatic report generation in the national monitoring module

3 Platform application

Shibei District, Qingdao City is taken as an example for monitoring of urban road network reliability. Shibei District of Qingdao is a peninsula, with external corridors constrained by the sea and terrain. The terminal-type road network restricts traffic circulation, leading to tight corridor resources. It is necessary to identify critical road segments and prioritize their connectivity to improve the structural reliability of road network. In addition, transportation demand in Shibei District is relatively concentrated, and natural conditions determine that the road network supply is limited. Therefore, it is necessary to identify key areas of supply–demand imbalance and conduct demand allocation. The platform is used to calculate the structural reliability, operational reliability, and capacity reliability of the road network in Shibei District. Some calculation and analysis results are shown in Fig. 8.

From the assessment results of road segment importance, it is observed that the importance of radial corridors linking the core area to the peripheral areas is high, such as Huayang Road–Chongqing South Road and Xinguan Elevated Road–Huanwan Road. The assessment results for structural reliability of road network reveal that the structural reliability of some inter-district fast corridors and internal fast contact corridors is low, such as Hang'an Elevated Road–Huanwan Road, Jiaoning Elevated Road, and Cross-sea Bridge

Elevated Road. The assessment results of operational reliability show that there are unreliable roads at three levels: zones, corridors, and nodes. At the zone level, the overall travel time reliability of the Qingdao CBD zone is not high; at the corridor level, there are "two horizontal and one vertical" unreliable corridors, including Hang'an Elevated Road–Liaoyang West Road, Jiaoning Elevated Road (Yan'an 1st Road–Shandong Road), and Shandong Road (south of Yanshan Overpass); at the node level, the path time reliability of nodes, such as Yanji Road–Shandong Road intersection and Huaiyuan Road–Heilongjiang South Road intersection, is poor. From the assessment results of reliability on road network capacity, it is evident that the capacity reliability of zones such as the old town of the Shibei District, Qingdao Shibei Experimental Elementary School, and Qingdao Yuxian Middle School is low, requiring focused optimization of road supply conditions.



a. Road grid structure reliability

b. Road network time reliability

Fig. 8 Results of road network reliability assessment in Shibei District, Qingdao

4 Conclusion

Real-time and rapid monitoring on urban road network reliability is an important guarantee for achieving precise traffic governance in cities and the construction of resilient cities. The platform for monitoring national–urban road network reliability, designed and developed to meet the monitoring needs of both national and city levels, has established a comprehensive assessment indicator system that includes structural reliability, operational reliability, and capacity reliability. It conducts systematic assessment from three dimensions: road facilities, traffic operating status, and traffic carrying capacity. By breaking through the method of indicator computation based on massive big data and applying indicators to the reliability assessment of real large-scale road networks, the platform provides technical support for improving road network reliability. Due to data limitations, the platform mainly conducts reliability assessments of the normal operation of road networks. Major traffic incidents, natural disasters, extreme weather, and other events that significantly impact road network operations during operation have not been considered. In the future, with relevant data and research related to road network resilience, the platform's functionality can be further improved and enriched.

References

[1] MINE H, KAWAI H. Mathematics for reliability analysis [M]. Tokyo: Asakura-shoten, 1982.

[2] SIU B W Y, HONG K L. Doubly uncertain transportation network: degradable capacity and stochastic demand [J]. European Journal of Operational Research, 2008, 191 (1): 166–181.

[3] CHEN A, YANG H, HONG K L, et al. Capacity reliability of a road network: an assessment methodology and numerical results [J]. Transportation Research Part B: Methodological, 2002, 36 (3): 225–252.

[4] WANG D H, QI H S, XU C. Reviewing traffic reliability research [J]. Journal of Transportation Systems Engineering and Information Technology, 2010, 10 (5): 12–21 (in Chinese).

[5] XU B C. Urban road network reliability measurement based on traffic state [D]. Nanjing: Southeast University, 2021 (in Chinese).

[6] HU B, YUE Y, LI Q Q. With the analysis of structural form of network evaluation index based on complex network [J]. Journal of Geomatics, 2013, 38 (3): 5–8 (in Chinese).

[7] TANG X R, CHEN Y Y. Relationship between accident deposing time and network recovery reliability [J]. Journal of Transportation Systems Engineering and Information Technology, 2009, 9 (5): 124–129 (in Chinese).

[8] CHENG YD, AN R. Road network reliability analysis based on taxi GPS data [J]. China Transportation Informatization, 2014 (12): 141–143 (in Chinese).

[9] FANG Y J, ZHENG C J, MA G H, et al. Reliability analysis of road network capacity based on service level constraints [J]. Journal of Wuhan University of Technology (Transportation Science & Engineering), 2019, 43 (3): 502–504 (in Chinese).

[10] CHENG W, ZHANG D M, XIAO H C. Research on dynamic traffic simulation and evaluation system of road network reliability [J]. Journal of System Simulation, 2013, 25 (12): 2986–2992 (in Chinese).