Research on the Application of Vehicle-Infrastructure Interaction Control Domain for Tourist Trunk Highways in Cold Regions

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Abstract. Addressing issues such as inadequate spatiotemporal adaptability of roadside control, low data matching accuracy, weak beyond-line-of-sight (BLOS) service capabilities, and a lack of adaptability in integrated traffic-tourism scenarios in vehicle-infrastructure interaction applications for tourist trunk highways in cold regions, this study comprehensively considers core factors including road geometric features, traffic operation environment in cold regions, differentiated control service distances, and traffic-tourism integration service demands. A high-precision feature identification map data model suitable for roadside services is constructed. Vehicle-infrastructure interaction application scenarios coupling "user, demand, topology, seasonal frost characteristics, and traffic-tourism integration" are designed. A calculation method for the dynamic scope of traffic control services is proposed. By integrating multi-source spatio-temporal data, a roadside spatiotemporal benchmark data model for vehicle-infrastructure interaction is established. A traffic control service system with spatial-temporal adaptability and an interactive information content system for traffic-tourism integration are developed, and conducted an analysis on the technological acceptance of interactive information based on the XGBoost regression method. This research aims to solve problems such as spatial calculation of traffic control, precise data matching, optimization of information service efficacy in BLOS roadside environments, and coordination of traffic-tourism integration services. The goal is to achieve precision, low-latency, and intelligent upgrades of roadside interactive services in cold regions, as well as the integrated implementation of traffic-tourism integration services, thereby providing a technical pathway for the engineering application of vehicle-infrastructure interaction on trunk highways in cold regions.

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1 Introduction

The iteration of new-generation information technologies, including cloud computing, the Internet of Things (IoT), and big data, has propelled the evolution of traffic information computation from standalone independent modes to distributed big data processing modes. The rapid implementation of vehicle-infrastructure interaction technologies and the widespread adoption of intelligent vehicle-mounted/mobile terminals, coupled with the practical demands for integrated transportation and tourism development on trunk highways in cold regions, all have imposed higher requirements for the intelligence, timeliness, and scenario-specific nature of roadside services. Low-latency, scenario-adaptive roadside computing models have emerged as one of the core focal points for enabling the synergy between vehicle-infrastructure interaction and traffic-tourism integration.

The spatiotemporal data model for traffic control services constitutes a critical foundation for the implementation of roadside computing paradigms. Current research predominantly focuses on the storage and organizational logic of geographic data itself[1]. In the practice of vehicle-infrastructure interaction , a unified application is achieved by loading high-precision maps on the vehicle side and three-dimensional scenes on the platform side[2]. However, there are notable shortcomings in the application of roadside high-precision maps: First, these maps fail to integrate traffic spatiotemporal strategic data related to incidents, special environments in cold regions, and dynamic vehicle operating conditions. Second, insufficient consideration has been given to the impact of matching dynamic traffic control information with reference objects within the communication range of intelligent roadside facilities. Third, there is an absence of adaptive design for special scenarios such as icy/snowy surfaces, low visibility, and heavy rainfall, as well as for peak-season traffic services, making it difficult to meet the demands of coordinated vehicle-infrastructure interaction and traffic-tourism integration on ordinary trunk highways in cold regions.

Based on this, this paper takes ordinary trunk tourist highways in cold regions as the object, constructs a roadside service-oriented high-precision feature identification map data model, studies the calculation method for the dynamic spatiotemporal domain of traffic control services, and integrates them to form a vehicle-infrastructure interaction roadside spatiotemporal reference data model adapted to cold regions. It incorporates the service requirements of transportation and tourism integration to design typical application scenarios, establishes an integrated interactive information system that combines traffic control and traffic-tourism services, and provides technical support for the engineering application of coordinated development between roadside interactive services and traffic-tourism integration in cold regions.

2 Research Overview

The core requirement of roadside interactive services boils down to achieving low-latency, refined, and highly time-sensitive traffic control and information distribution. The integration of cross-node multi-source spatiotemporal traffic data based on roadside high-precision map data serves as a digital foundation for localized domain calculation and the generation of differentiated control strategies on the roadside. It provides control and decision support for applications such as vehicle-infrastructure interaction information services, intelligent driving, and the integrated services.

As an important component of the regional transportation network, ordinary trunk highways in cold regions fulfill the dual purposes of transportation and tourism[3-4]. Lined with ice and snow scenic spots, folk custom tourism sites, and outdoor leisure destinations, these arteries experience significant passenger flows during both the winter ice-and-snow tourism season and the summer ecotourism season, creating an urgent need for integrated transportation-tourism development. However, traffic control on trunk highways in cold regions is challenging due to environmental factors such as seasonal frost, ice, snow, and low visibility. Coupled with the significant differences in driving characteristics and service demands between tourist flows and ordinary vehicle flows, traditional traffic control models struggle to accommodate the diversified service demands of an integrated transportation-tourism system.

In response to the deficiencies of existing spatiotemporal data models in roadside applications in cold regions and considering the demand for the development of traffic-tourism integration, this study explores the application of vehicle-infrastructure interaction management and control domains in tourism trunk highways in cold regions. The research includes the following aspects: First, a high-precision feature identification map data model adapted to roadside edge services is constructed to enable localized storage, dynamic updates, and cross-facility collaboration of high-precision map data. Second, by integrating the seasonal frost characteristics of cold regions with the needs of traffic-tourism integration, typical vehicle-infrastructure interaction application scenarios are established through coupling "user, demand, topology, seasonal frost characteristics, and traffic-tourism integration," achieving precise alignment between scenarios and the dual demands of traffic and tourism in cold regions. Third, a dynamic spatiotemporal domain calculation method for traffic management and control services is proposed. This method integrates multi-source data to construct a spatiotemporal reference data model and establishes an integrated vehicle-infrastructure interaction information system with spatiotemporal adaptability for traffic management and control services and traffic-tourism integration. This approach addresses key challenges such as BLOS roadside management and control in cold regions, high-precision data matching, and collaborative services for traffic-tourism integration, thereby enabling refined traffic services on trunk highways based on traffic-tourism integration applications.

3 Construction of High-Precision Feature Identification Map Model

High-precision feature identification map data serves as the core spatial object for roadside intelligent facilities to conduct localized traffic management and distribute strategies for traffic-tourism integration services. It encompasses point, line, and area spatial objects such as road markings, lanes, structures, and monitoring facilities across different time cycles[5], as well as spatial objects related to traffic-tourism integration, including tourist attractions, service stations, viewing platforms, parking lots, and restrooms. Its attribute data includes object type, identification of affiliated intelligent roadside facilities, spatial relationships, service capacity, and passenger flow capacity. The model construction adheres to the principles of physical segmentation, facility integration, hierarchical updating, and integration of traffic-tourism elements. It processes high-precision data of the road and traffic-tourism integration service data into the smallest physical segments divided by feature units, enabling collaborative management of physical and logical data.

3.1 Collection of High-Precision Map Data and Traffic-Tourism Integration Feature Data

A multi-source data integration approach—integrating 3D measurable real-scene imaging, radar scanning, and UAV aerial surveying—is employed to acquire foundational data, including road geometric alignments, facility layouts, and pavement markings, as well as tourism-related points of interest along the route such as scenic spots, service stations, viewing platforms, parking lots, restrooms, and emergency rescue points. The collected data are then standardized by assigning attributes—including object type, logical relationships, and timeliness indicators, along with tourism-specific attributes such as service type, service radius, passenger flow capacity, and operating hours—to form a standardized dataset that integrates high-precision map data with traffic-tourism integration features.

3.2 Edge-Side Preprocessing of High-Precision Map Data

Physical segmentation of the high-precision map data is performed using structural feature points as the dividing basis, in conjunction with the upstream/downstream direction of the road. The feature points encompass terrain change points, geometric alignment inflection points, service area entrances and exits, intersections, etc. After segmentation, a high-precision map dataset is formed: $A_{map}=\{S_{nmz}|(n,m,z)\}$, where z represents the road network code, m denotes the route code within road network z, n signifies the serial number of the physically segmented small road section within route m, and Snmz indicates the dataset of the n-th physically segmented section of the route with code m within road network z. The preprocessed data enables refined segmentation of the map, laying the foundation for localized data loading of roadside facilities.

3.3 Integration Processing of Service Scope of Roadside Facilities with High-Precision Maps and Traffic-Tourism Service Data

The identification map data is used by roadside intelligent facilities to provide spatial objects required for localized traffic control and service strategy distribution. These spatial objects include road signs and markings, lanes, road structures, monitoring facilities, safety facilities, and related facilities of the road in the form of points, lines, and surfaces under different time periods. The attribute data of spatial objects includes object type, identification of the intelligent roadside facility to which it belongs, spatial relationships, etc. The identification map is segmented according to the deployment location of intelligent roadside facilities and the spatiotemporal range calculated by intelligent roadside facilities, and the high-precision road data is processed to form the smallest physical segments divided by feature units. Physical data are visual objects that exist in the real world, while logical data are non-physical entity objects required for localized processing or strategy distribution.

Based on the communication capabilities of intelligent roadside facilities, the spatial coverage C_{rij} of a single facility E_i is defined. GIS spatial overlay analysis is conducted with the high-precision map dataset A_{map} and the traffic-tourism integration feature dataset to ensure that A_{map} and traffic-tourism integration data are either entirely or partially included within the scope of C_{rij}. This determines the stake numbers K_i for facility placement and the stake number set $K'=\{K_{ij}|(i,j)\}$ for communication unit locations, while achieving precise matching between traffic and tourism spaces.

Data loading and coding are performed according to the principles of full coverage, overlapping loading, and traffic-tourism collaboration. High-precision physical map data and traffic-tourism integration feature data within the coverage range of facility E_i at location K_i are encoded as E_iS_{nmz}-T (where T denotes the identifier for traffic-tourism integration data) and assigned the identifier attribute E_i. If there is an overlapping coverage area between adjacent facilities E_i and E_{i+1}, the data in the overlapping area is encoded separately as E_iS_{nmz}-T&$E_{i+q}S_{nmz}$-T (where q represents the number of overlapping areas) and loaded into both facilities with corresponding identifier attributes assigned, thereby enabling dual-node data backup, collaborative invocation, and integrated distribution of traffic-tourism information in the overlapping area.The deployment of the physical segmentation model for high-precision maps in cross-range environments or tunnel settings is illustrated in Figure 1; the model deployment based on partial coverage of intelligent roadside facilities E_1, E_2, ..., E_{n-1}, E_n is depicted in Figure 2.

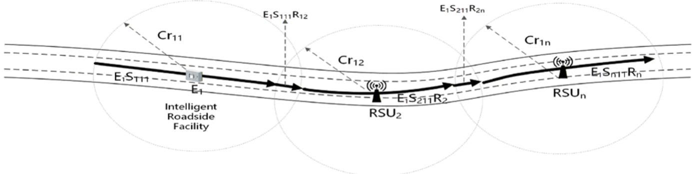

Fig. 1. Deployment of high-precision map physical segmentation model in environments beyond visual range or tunnel environments

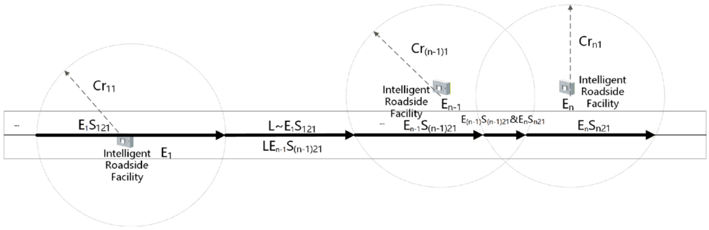

Fig. 2. Model deployment based on partial coverage of intelligent roadside facilities

3.4 Hierarchical Update of Roadside High-Precision Map Data Model

A three-level hierarchical update system, encompassing roadside-road section (route/corridor)-center (region), is constructed to achieve real-time, synchronized, and precise updates of traffic data and traffic-tourism integration data. Updates of the high-precision roadside map data model are organized at a roadside-section (route/passage)-center (region) level, as shown in Figure 3. The organization of spatiotemporal data covers four core elements: object type, storage form, spatial logical relationship, and transmission data format[6-10]. Among them, the traffic-tourism integration data introduces a dynamic update dimension, facilitating the real-time synchronization of dynamic information—such as the operational status of tourism facilities, passenger flow density, and parking availability.

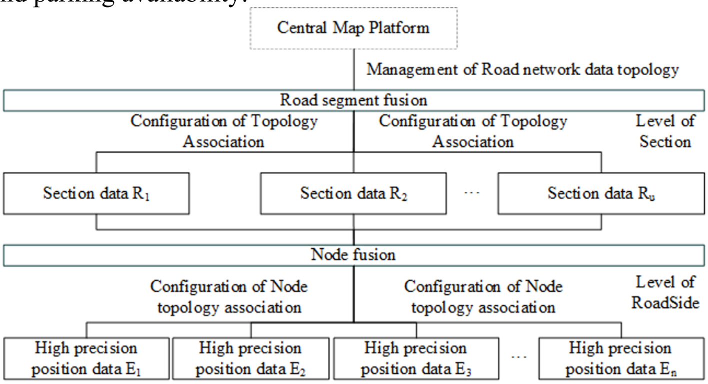

Fig. 3. Spatio-temporal data organization and update structure

(1) Storage form: It includes configuration information such as the local storage environment, data format, distribution nodes, node relationships, and application interfaces of roadside intelligent facilities.

(2) Data transmission: Standardized data encoding forms such as ASN.1, GML, and GeoJSON are adopted to ensure compatibility in cross-facility and cross-level traffic data transmission[11-16].

By establishing spatial logical associations among roadside-level high-precision location maps E1 to En, real-time updates of traffic-tourism integration data based on facility locations are achieved. By establishing spatial logical correspondences between road section/route-level data R1 to Ru, integration and synchronous updates with road-side-level data are realized, ensuring the authenticity, validity, and accuracy of data across all levels.

4 Construction Method for Typical Vehicle-Infrastructure Interaction Application Scenarios in Cold Regions

To meet the travel demands of tourists and operators of key commercial vehicles, this study constructs several application scenarios: risk early warning for traffic incidents in frost weather, collaborative management and information service for tourism traffic, and emergency rescue in extreme weather events. Considering the seasonal frost characteristics of cold regions and the service demands for the traffic-tourism integration on trunk highways, a framework of "user, demand, topology, seasonal frost characteristics, and traffic-tourism integration" is proposed for scenario construction. This framework achieves precise alignment between scenarios and the dual demands of traffic management and tourism services in cold regions, addressing issues such as the gap between generalized demands and practical implementation, and the fragmentation of tourism services. The principles for scenario construction are as follows:

(1) Principle of demand orientation: Identify the core pain points of different users to ensure a high degree of alignment between scenarios and demands. For instance, highway management departments are concerned with network resilience and traffic safety, maintenance units focus on cost efficiency, and transportation enterprises prioritize transit timeliness.

(2) Principle of seasonal frost regions and traffic-tourism integration characteristics: Incorporate factors such as freeze-thaw cycles, icy/snowy pavements, and ice-and-snow attractions to avoid the inadequacy of generic scenarios in these specific contexts.

(3) Topology-empowerment principle: Utilize corridor and network topology indicators (dynamic betweenness, node vulnerability, connectivity resilience, etc.) as core data, transforming topological analysis results into decision-making bases that are perceivable and operable by users.

(4) Dynamic adaptation principle: Consider the seasonal variations across frost regions, such as "winter freezing and spring thaw settlement," to construct dynamic scenarios for different time periods, thereby meeting user demands across seasons.

4.1 Precise Depiction of User Personas

To avoid vague user positioning, user personas represent the starting point for scenario construction and should be depicted from four dimensions: identity attributes, decision-making authority, core demands, and pain points.

In terms of identity attributes, users can be classified into administrative users (highway bureaus, maintenance units), operational operators (freight enterprises, passenger transport companies), and individual travelers (private car owners), each with varying decision-making authority regarding resource allocation. Their demands are further distinguished between rigid and flexible needs—for instance, freight enterprises prioritize avoiding high-risk frost-damaged sections and ensuring transit time as rigid demands, while minimizing fuel costs represents a flexible demand. In terms of pain points, the primary concern for administrative users is ensuring timely warning and control when critical corridors face major risks or disruptions due to icy and snowy weather. For freight enterprises, the pain points center on vehicle breakdowns caused by frozen roads, long downhill sections, and sharp curves with steep grades, which in turn increase transportation delays.

4.2 Demand Deconstruction in Seasonally Frozen Regions

This process involves transforming generalized demands into specific indicator requirements. Given that users' initial demands are often broad (e.g., "enhance road network resilience" and "reduce risk costs"), it is necessary to dissect these demands into quantifiable and actionable elements by considering the characteristics of seasonally frozen regions, and to clarify the corresponding seasonal frost impact factors.

A three-tier deconstruction method of "objectives-means-constraints" is adopted. At the objective level, it refers to the core objectives of users (e.g., "improve the emergency traffic assurance capacity of the road network in winter"). At the means level, it involves specific means to achieve these objectives (e.g., "rapidly identify key road sections with high-risk and issue warning information"). At the constraint level, it encompasses the special constraints of seasonally frozen regions (e.g., "a 30% reduction in traffic capacity on icy road sections and sharp bends and steep slopes, and limited de-icing resources during snowy and icy weather").

4.3 Topological Element Mapping and Matching

Establishing a corresponding relationship among "demand, topological indicators, and algorithms" serves as the core link in scenario construction. Based on the results of demand deconstruction, appropriate topological indicators and algorithms are selected to avoid the disconnection between indicators and demands. A "demand, indicator, and algorithm" mapping table is formed to clarify the core indicators, calculation methods, and data sources corresponding to each demand.

4.4 Scenario Dimension and Rule Setting

The operational boundaries and closed-loop processes of scenarios are defined. After completing element matching, clarify the dimensional attributes and operational rules of scenarios to form a scenario plan that can be directly implemented.

Scenario dimension setting requires clarifying the three core dimensions of scenarios to ensure their uniqueness and pertinence: (1) User dimension: define the specific user groups; (2) Seasonal dimension: determine the applicable seasons for scenarios; and (3) Functional dimension: clarify the core functions of scenarios (e.g., "emergency traffic assurance," "precision maintenance," and "route planning").

The establishment of scenario operation rules encompasses several key elements: (1) triggering conditions—signals that initiate the scenario; (2) input data—the foundational data required for scenario operation (e.g., topological models, traffic flow data); (3) operational procedures—clearly defined, phased steps (e.g., the three-stage process of "pre-control, handling, and review"); (4) output results—the decision-making products delivered upon scenario completion; and (5) closed-loop scenario design—ensuring a closed-loop process of "input, processing, output, and feedback" within the scenario.

4.5 Dynamic Validation and Iterative Optimization

To enhance the practical adaptability in specific scenarios, dynamic validation and iterative optimization are conducted. This involves verifying scenarios through practical applications and continuously refining them to address discrepancies between "theoretical scenarios" and "practical applications." Validation methods may include case studies and user feedback, while iterative optimization may encompass metric optimization (adjusting metric weights), process optimization (streamlining operational steps), and dimensional expansion (adding new user dimensions).

4.6 Examples of Application Scenarios

Based on the aforementioned scenario construction methodology, three typical scenario examples have been designed to cater to the needs of trunk highways in cold regions, in order to achieve an integration of traffic management and tourism services.

(1) Risk Early Warning Scenario for Traffic Incidents in Icy Weather

Applicable Period: Winter periods characterized by low temperatures, snowfall, and icy road surfaces.

Triggering Conditions: Road surface temperature ≤ 0°C, ice thickness ≥ 2mm, road friction coefficient below the safety threshold, and tourist vehicles entering high-risk road sections.

Core Functions: 1) Real-time perception and graded early warning of road icing conditions; 2) prioritized identification of tourist vehicles and lane-specific risk warnings; and 3) advanced safety reminders at entrances to tourism facilities, viewing platforms, and parking areas along the route.

Vehicle-Infrastructure Interaction Information Output: 1) Ice warning on the road ahead, with recommended speed limit and cautious lane change; 2) Advice for tourist vehicles: slow down, no overtaking, proceed to nearby service area; and 3) Real-time updates on accessible tourist routes and closure of ice-and-snow viewing platforms along the route.

Management and Control Objectives: Reduce the accident rate of tourist traffic on icy road sections, thereby achieving risk anticipation, vehicle-infrastructure interaction, and integrated traffic-tourism management.

(2) Collaborative Management and Information Service for Traffic-Tourism Scenarios

Applicable Period: Peak travel periods during tourist seasons, holidays, and weekends.

Triggering Conditions: Exceeding the carrying capacity of tourist attractions, saturation of traffic on trunk highways, the need for tourism passage on icy road sections, and concentrated passage of tourist buses.

Core Functions: 1) Collaborative diversion and staggered peak control of tourist traffic flow and social traffic flow; 2) Real-time notification of remaining parking spaces in scenic areas and tourist flow density; 3) Dynamic service for tourist routes and priority passage guidance.

Vehicle-Infrastructure Interaction Information Output: 1) Real-time tourist flow in scenic areas, remaining parking spaces, and queue times at entrances; 2) Locations and statuses of service stations, viewing platforms, and restrooms along the route; 3) Real-time information on service area energy supply (fuel and charging stations).

Management and Control Objectives: Achieve integrated traffic management and tourism services to enhance the experience and efficiency of traffic-tourism integration on trunk highways.

(3) Emergency Rescue Scenarios for Extreme Weather Conditions

Applicable Periods: Sudden situations such as snowstorms, freezing fog, road icing and closures, and traffic accidents.

Triggering Conditions: Temporary road closures, vehicle stranding, tourist bus entrapment, visibility < 50m in foggy conditions, and icy-road-related traffic accidents.

Core Functions: 1) Comprehensive monitoring of extreme weather conditions with rapid implementation of road closures and speed limits; 2) Locating trapped vehicles/tourists and planning rescue routes; 3) Dissemination of information on nearby emergency shelters, rescue stations, and warming shelters; 4) Cross-departmental collaborative emergency dispatching .

Vehicle-Infrastructure Interaction Information Output: 1) Mandatory instructions: road closed, no entry, pull over immediately; 2) Rescue point locations, evacuation routes, and contact numbers for stranded vehicles; 3) Information on temporary scenic area closures, tourist evacuation, and shuttle services.

Management and Control Objectives: Ensure the safety of tourist vehicles and occupants during frost/extreme weather conditions and achieve rapid emergency response through vehicle-infrastructure interaction.

5 Calculation Method for the Dynamic Action Scope of Traffic Control Services

Based on the high-precision feature identification map data model and integrating the linear reference model theory[17], we construct a logical relationship for multi-node spatiotemporal data across roadside facilities. Considering factors such as the impact of dynamic traffic events, the superimposed effects of passenger and vehicle flows resulting from the traffic-tourism integration, and the varying distances for differentiated control services, we propose a method for calculating the dynamic scope of traffic control services through "multi-node collaboration, event/passenger flow range analysis, and control domain calculation." This approach enables precise and dynamic delineation of control domains while accommodating complex scenarios characterized by the superimposition of passenger and vehicle flows under the traffic-tourism integration.

5.1 Multi-Node Dynamic Spatiotemporal Data Coordination

Identify and extract dynamic spatiotemporal data, such as risk sections and sections around high-tourist-flow scenic areas, based on road foundation spatial data and traffic-tourism integration feature data. According to the dynamic segmentation theory, set the reference point coordinate value at the stake number Ki where the intelligent roadside facility Ei is located as Rd, and calculate the linear reference coordinate sequence of the road section within its coverage: R_c={r1,r2,…,rg}, where g is the number of linear reference coordinate points meeting the needs of traffic control and traffic-tourism integration service applications within the coverage spatiotemporal scope, and rg is the g-th linear reference coordinate value.

The dynamic spatiotemporal reference data (including traffic and traffic-tourism integration data) acting on E_i is labeled as E_iR_c-T (where T represents the identifier for traffic-tourism integration data). For overlapping coverage areas of adjacent facilities, their dynamic spatiotemporal reference data is labeled as $E_iR_c-T\&E_{i+q}R_c-T$, enabling dual-node dynamic invocation of data in overlapping regions. Based on traffic control service distance, traffic-tourism integration service radius, and time-effect parameters, a highly reliable data transmission mechanism is established across facility nodes from E_1 to E_n, achieving collaborative linkage of spatiotemporal data for traffic and traffic-tourism integration across multiple nodes.

5.2 Spatial Scope Analysis Considering the Superimposed Impact of Dynamic Traffic Events and Tourist Flows

Based on the spatial information of intelligent roadside facilities, precise matching is performed between the locations of traffic incidents and abnormal tourist flow events and the storage/associated road segments of the facilities. The original stake number location of the event is calculated as: K_{Event_ih}={f(E,E_y), f'(Ex,E_y)}, where Ex and E_y represent the longitude/latitude or planar coordinate values of the roadside facility, f(E,E_y) and f'(E_x,E_y) represent the stake number values of the event's starting and ending points corresponding to the coordinates, h is the type number of the traffic/tourism event perceived by facility E_i, and T is the identifier for tourism events.

Combining the initial impact scope of the event and the abnormal diffusion scope of tourist flows, the original spatial data of the event's integrated impact scope is calculated as: EventScope-T={NodeList, LinkList, PolygonList}. Here, NodeList represents a spatial coordinate list of the traffic-tourism integration, LinkList represents a list of spatial geometric line layers, and PolygonList represents a list of spatial geometric surface layers. Using event impact/diffusion models and tourist flow propagation models, the spread speed of the traffic event (E_{speed}) and the diffusion speed of the tourist flow (T_{speed}) per unit time are calculated, yielding the dynamic impact scope of the traffic-tourism integration event at time t: tEventScope-T={EventScope-T+f(EventScope-T, $t*E_{speed}+t*T_{speed}$)|t∈R}.

A layer EiScope is generated for the signal coverage area C_{rij} of facility E_i. Through GIS spatial overlay analysis, the overlapping area EVScope-T between the impact scope of the traffic-tourism integration event and the coverage scope of the facility is obtained, forming a dynamic spatial scope data model for traffic-tourism integration. This provides a composite event spatial boundary basis for the calculation of the control domain.

5.3 Calculation of the Dynamic Action Scope of Traffic Control Strategies

First, access multi-source heterogeneous monitoring data from transportation and tourism sectors, including traffic flow, traffic incidents, meteorological conditions, vehicle movement, vehicle condition, road surface conditions, infrastructure status, emergency management and control, passenger flow in service areas, tourism facility status, and tourism travel trajectories. Second, integrate and identify various abnormal event sets: {WED_{tmi}, WED_{tfi}, WED_{tpi}, WED_{tsi}, TED_{tki} | WED_{tmi} ∈ ED_{tmi}, WED_{tfi} ∈ ED_{tfi}, WED_{tpi} ∈ ED_{tpi}, WED_{tsi} ∈ ED_{tsi}, TED_{tki} ∈ TD_{tki}}, where TED_{tki} represents tourism abnormal event data, and TDtki denotes the tourism abnormal event dataset. Third, calculate the location information {K_{mi}, K_{fi}, K_{pi}, K_{ki}} of the traffic-tourism event set and their dynamic impact ranges: DR-T = {{DK_{mi}, $SPEED_{mi}$}, {DK_{fi}, $SPEED_{fi}$}, {DK_{pi}, $SPEED_{pi}$}, {DK_{ki}, $SPEED_{ki}$}}. Here, K_{ki} represents the location of tourism abnormal events, and $SPEED_{ki}$ denotes the diffusion speed of tourism abnormal events. Finally, through superimposed analysis of DR-T elements, the mileage set AL = {L_{mi}, L_{fi}, L_{pi}, L_{ki}} from facility E_i to the boundaries of each traffic-tourism incident area is obtained.

By integrating high-precision map data, traffic-tourism integration characteristic data, and high-precision location matching technology, identify the road data and tourism service data carried by facility E_i, and recognize adverse/risky road sections and sections with high passenger flow control requirements. Based on the dynamic impact range of traffic-tourism integration events at time t, denoted as tEventScope-T, and the real-time driving positions of vehicles, generate differentiated traffic strategy prompts, tourism guidance warning data, and control measure data. By integrating tEventScope-T with the facility coverage layer E_iScope, the model for the dynamic scope of traffic control strategies is ultimately derived: STRATEGYScope-T = {(tEventScope-T, E_i-Scope) | i ∈ N, t ∈ R}, enabling real-time adjustments of the control scope in response to transportation events, tourism events, vehicle movement, passenger flow diffusion, and service facility supply coverage.

6 Construction of Interactive Information and Analysis of Acceptance Degree for Traffic Control and Traffic-Tourism Integration in Cold Regions

Centered on the dynamic scope of traffic control services, this study employs correlation analysis and spatial overlay techniques to deeply integrate traffic incident data, tourism event data, event impact range data, control service distance data, traffic-tourism integration service radius data, and the spatial locations of roadside facility nodes. This integration facilitates the construction of an integrated service system for traffic control and traffic-tourism integration in cold regions, which possesses spatiotemporal adaptability. The system establishes rules for generating control strategies, defines the information of traffic-tourism integration interaction, and implements a differentiated dissemination mechanism, thereby achieving precise control over tourism trunk highways in cold regions and delivering information service for traffic-tourism integration.

6.1 Intelligent Generation Rules for Traffic Control and Traffic-Tourism Integration Service Strategies

Based on the results of spatiotemporal overlay analysis, the types of traffic-tourism integration scenarios that roadside facilities E1 through En need to implement at time T are intelligently identified. A dataset of traffic-tourism integration control service strategies is then automatically assembled, encompassing speed limits, early warnings, tourism information guidance, energy supply services at service areas, and coordinated passenger flow scheduling. The strategy generation follows the principles of priority-based control, value optimization, and transportation-tourism collaboration:

(1) Speed limits: Denote the y-th set of speed limits for the s-th consecutive road section as Speedlimit−s[y]. The final speed limit value is taken as the minimum value of the set, i.e., $\text{Speedlimit}-\text{s} = \min\{\text{Speedlimit}-\text{s}[\text{y}] \mid \text{y} \in \text{N}\}$. The priority of speed limit values is as follows: dynamic traffic speed limit values > static speed limit values of traffic infrastructure > road design speed limit values.

(2) Strategy processing: This involves the collaborative processing of traffic control strategies and traffic-tourism integration service strategies. The strategy content is organized logically according to emergency rescue, traffic control, tourism passenger flow guidance, traffic warnings, tourism information prompts, route diversions, and tourism service support. When multiple strategies coexist within the same spatiotemporal scope, they are prioritized as: emergency rescue > traffic control > tourism passenger flow guidance > traffic warnings > tourism information > route diversion > tourism service support. Dynamic strategies always override static ones.

6.2 Information Content of Traffic-Tourism Integration under Vehicle-Infrastructure Interaction

By integrating the traffic operation characteristics of ordinary trunk highways in cold regions with the service demands of traffic-tourism integration, a hierarchical and classified vehicle-infrastructure interaction information content system with traffic-tourism collaboration has been established. This system ensures precise alignment between information content and traffic management and control strategies, tourism service strategies, and integration scenarios in cold regions, forming categories such as traffic environment perception, traffic safety warning, traffic management and control instructions, basic tourism information, dynamic tourism services, traffic-tourism integration collaboration, and emergency rescue coordination. Among them, the traffic environment perception includes special traffic environment information in cold regions, such as pavement temperature and snow/ice thickness; the traffic safety warning encompasses traffic warning information for high-risk icy and snowy road sections, accident-prone sections, and sections with facility failures, as well as reminders for abnormal vehicle driving behaviors; the traffic management and control instructions include real-time traffic management and control instructions, such as speed limits and prohibitions, as well as emergency traffic control information; the basic tourism information covers fundamental tourism information, such as the locations, opening hours, available services, and ticket information of scenic spots, service stations, viewing platforms, parking lots, and restrooms along the route; the dynamic tourism services include real-time service information, such as passenger flow density, real-time parking availability, the operational status of service stations, energy supply status, and the traffic capacity of tourist routes; the traffic-tourism integration collaboration includes collaborative information such as tourist route planning matched with traffic conditions, traffic diversion suggestions corresponding to passenger flow guidance, and traffic management and control tips around scenic spots during peak tourist seasons; the emergency rescue coordination includes coordinated information such as rescue routes for traffic/tourism emergencies, information on shelters for trapped vehicles/tourists, emergency support information from nearby service stations/scenic spots, and severe weather safety warnings for cold regions.

Based on the integrated vehicle-infrastructure interaction service information, spatiotemporal adaptation of information dissemination in traffic-tourism integration scenarios has been implemented to achieve precise matching between the timing, scope, and content of information dissemination and the progression of traffic incidents, the spread of tourism events, changes in spatiotemporal environments, and the real-time locations of vehicles/tourists. Meanwhile, considering the seasonal frost characteristics of cold regions, dynamic adjustments have been made to the frequency and coverage of information dissemination during the winter ice and snow tourism period and the summer tourism period, thereby enhancing the timeliness and effectiveness of integrated traffic-tourism information services.

6.3 Analysis of Acceptance of Interactive Service Technology on Trunk Highways in Cold Regions

Through research on vehicle-infrastructure interaction scenarios and spatiotemporal adaptation for trunk highways in cold regions, combined with the traffic operation characteristics of tourist trunk highways in seasonal frost regions, a survey questionnaire tailored for travelers on ordinary trunk highways in cold regions was designed. The questionnaire included 22 items organized into five sections: demographic and travel-related information, current service satisfaction, service needs, precision and adaptability demands, and smart technology acceptance.The perceptual items used a five-point Likert scale ranging from 1 ("strongly disagree" or "very low demand/satisfaction") to 5 ("strongly agree" or "very high demand/satisfaction").

The questionnaire includes 22 items: Q1_Age group; Q2_Travel frequency on tourist roads in cold regions in the past year; Q3_Level of understanding of the concept of vehicle-to-roadway communication; Q4_Overall satisfaction with traffic information services along the road; Q5_Receiving real-time traffic information ahead in adverse weather conditions; Q6_The traffic information is basically consistent with the actual road conditions; Q7_The content of information prompts is monotonous and lacks integration of tourism information; Q8_Being able to know dangerous situations in advance on roads with obstructed vision; Q9_It is difficult to obtain real-time dynamic information about parking areas in service zones; Q10_ I hope to receive early warnings about icy and snowy conditions for safety; Q11_ Hope to link traffic information with parking service area information in scenic spots; Q12_I hope to receive real-time route recommendations during peak hours; Q13_Hope to receive emergency guidelines during extreme weather; Q14_Is it necessary to provide differentiated services for tourist vehicles and ordinary vehicles; Q15_I hope information services can be precisely pushed according to road segment location and direction; Q16_The content and frequency of information services should vary across different seasons; Q17_I hope to receive suggestions on combining road information with attractions and service facilities; Q18_Trust and willingness to follow system-recommended speeds or control instructions; Q19_The current information service is not precise enough in terms of time, location, and content matching; Q20_Are you willing to receive real-time comprehensive information through in-vehicle systems or apps; Q21_Intelligent information services significantly enhance both security and user experience; Q22_Willing to accept the control prompts actively pushed by the system. The questionnaire was distributed to 300 respondents who had traveled on ordinary trunk highways in northeastern, northwestern, or northern China during winter or spring within the previous year.

(1) Variable Construction and Feature Engineering

Questionnaire items were aggregated into four features to improve interpretability and reduce dimensionality:F1 represents Demographics and Experience and was derived from Q1–Q3; F2 was computed as the mean of Q4–Q9 and represents Current Service Satisfaction; F3 was computed as the mean of Q10–Q14 and represents Service Needs; F4 was computed from Q15–Q19 and represents Precision and Adaptability; The dependent variable, smart technology acceptance, was defined as the mean of Q20–Q22.

(2) Model Selection and XGBoost Regression Framework

However, the findings may suggest that linear regression was used as a baseline because of its transparency, ease of interpretation, and suitability for examining approximately linear relationships between explanatory variables and the target outcome. Additionally, the significant results could indicate that XGBoost regression was selected as the primary machine learning model because it might capture higher-order interactions among predictors while maintaining strong predictive performance on structured tabular data. Given that the evidence demonstrates that both models were employed, the study may suggest that this approach could allow comparison of a conventional interpretable baseline with a more flexible non-linear learning approach. Notwithstanding this comparison, the key findings may indicate that using both models appears to support a more comprehensive examination of the results.The optimization procedure suggest that 50 Optuna trials with 5-fold cross-validation on the training set could support reliable parameter selection, to identify the best-performing parameter combination for refitting the final XGBoost regression model. Additionally, the key evidence could demonstrate that model performance evaluation using R^2, MSE, RMSE, and MAE may support a balanced comparison between the interpretable linear baseline and the flexible predictive capacity of XGBoost.The research workflow is illustrated in Figure 4.

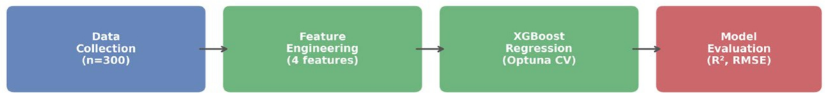

Fig. 4. Research methodology workflow

The results obtained through model calculations are shown in Figure 5.

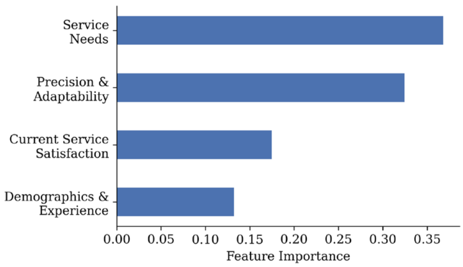

Fig. 5. XGBoost feature importance rankings

Figure 5 presents the feature importance rankings generated by the XGBoost model and provides significant insight into the relative contribution of the four explanatory variables. Moreover, the bar lengths shown in the figure may suggest that service needs (F3) is the most influential predictor, followed by precision and adaptability (F4), current service satisfaction (F2), and demographics and experience (F1). However, the findings could indicate that respondents' acceptance of smart V2I services appears driven primarily by what they expect the system to do for them, rather than by demographic characteristics. In light of the significant evidence, high importance for F3 may suggest that users attach strong value to concrete functional benefits such as safety warning dissemination, tourism–traffic information integration, route recommendation, and emergency guidance. Acceptance shows utility central to outcomes. The second-ranked position of F4 could further indicate that precision and adaptability are not peripheral concerns, but key determinants of acceptance in the ordinary tourist trunk highway context in cold regions. Thus, the findings may suggest that the operating environment appears characterized by snow, ice, low visibility, and rapidly changing road conditions, all of which could demonstrate the need for accurate, location-specific, and seasonally adaptive information delivery. This result is also consistent with the practical requirement that roadside interactive services on ordinary tourist trunk highways in cold regions should rely on high-precision feature identification data and multi-source spatiotemporal reference data to achieve precise matching among road sections, roadside facility coverage, dynamic events, and user-oriented service content. Furthermore, the results might indicate that F2, while still important, appears to play a somewhat weaker role than F3 and F4, suggesting that current dissatisfaction alone may not automatically translate into acceptance of new technology. Notwithstanding the significant results, the evidence could suggest that users must also perceive strong functional value and adaptive capacity in the proposed system for acceptance to follow. F1 shows age, frequency, familiarity less decisive. Moreover, the findings may suggest that the relatively low contribution of F1 implies that service-related perceptions appear more critical than demographic factors such as age, travel frequency, and familiarity with V2I concepts. In practical terms, the ranking F3 > F4 > F2 > F1 may suggest that, compared with traditional static traffic information release, users on ordinary tourist trunk highways in cold regions are more likely to value dynamic, scenario-oriented, and precision-based V2I service functions. Given that the evidence demonstrates a clear visual ranking, the results could indicate that Figure 2 supports the order F3 > F4 > F2 > F1. Therefore, the significant findings appear to demonstrate that internal consistency requires aligning the textual description with the visual ranking presented in the figure.

7 Conclusions

This study provides an innovative and comprehensive solution to the pressing challenges in cold-region tourist trunk highways, including inadequate spatiotemporal adaptability, low data matching accuracy, and weak beyond-line-of-sight service capabilities.Completed the research on matching spatial map data of trunk highway with roadside nodes and traffic control zones, core factors such as road geometric features ,conditions of extreme weather in seasonal freezing regions and traffic-tourism integration demands,which constitute complex traffic operating environments, have been taken into consideration.

The construction of a high-precision feature identification map data model ,the design of vehicle-infrastructure interaction scenarios tailored to cold regions and the proposed dynamic scope calculation method for traffic control services and the establishment of a spatiotemporal benchmark data model for vehicle-infrastructure interaction, applicable to tourist trunk roads,have solved issues such as inaccurate matching between roadside data and facility service coverages, as well as the fragmentation of traffic and tourism data and insufficient scenario adaptation service capabilities.From an application perspective, the ranking of F3 and F4 further suggests that V2I deployment on ordinary tourist trunk highways in cold regions should not focus only on infrastructure connectivity, but also on whether roadside systems can provide accurate, location-specific, and seasonally adaptive information services. This requirement is closely related to the use of high-precision feature identification data and multi-source spatiotemporal roadside reference data, which support precise matching among road sections, roadside facility coverage, dynamic traffic events, and traffic-tourism integration service content. In this sense, the present results not only identify user acceptance priorities, but also provide a user-oriented basis for determining which roadside service functions and data-support capabilities should be prioritized in practical deployment.

Furthermore, the key findings could indicate that these results provide empirical guidance for prioritizing V2I function design in deployments on ordinary trunk highways in cold regions. More specifically, the findings may suggest that user-oriented functions such as real-time safety warning, tourism-traffic information integration, route guidance, and emergency assistance should be treated as priority directions for roadside interactive service design. At the same time, the importance of precision and adaptability may indicate that effective deployment also depends on whether roadside systems can support accurate and adaptive information matching under changing environmental and traffic-tourism conditions. In this respect, the study provides a practical basis for roadside service scenarios, high-precision feature identification data, and multi-source spatiotemporal service support. Nevertheless, the significant limitations may suggest that the cross-sectional survey design, self-reported measures, and single-region sampling scope appear to constrain the evidence. In addition, the present study relied on 300 questionnaire responses and four aggregated explanatory features, which means that some potentially important factors such as individual risk perception, prior experience with intelligent roadside systems, were not directly incorporated into the model. Moreover, although the study linked acceptance analysis with practical roadside service scenarios, the application discussion remained primarily scenario-based rather than based on large-scale field deployment and continuous operational validation on ordinary tourist trunk highways in cold regions. Given that these results demonstrate important methodological constraints. Future studies may also integrate richer scenario-related variables and real-world deployment observations to improve both predictive accuracy and practical interpretability. Evidence shows broader sampling needed to support robust conclusions.

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