

From Fragmentation to Integration: A "Six-Domain" Systemic Framework for Multimodal Transport Connectivity

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Abstract: To address the problems of infrastructure fragmentation, non-unified standards and information silos in the connectivity of China's multimodal transport, as well as the incomplete modular decomposition of transport organization and hub layout in existing research, this study proposes a "One Core, Two Goals, Four Dimensions and Six Systems" framework for the core common technical systems of China's multimodal transport. We construct six technical subsystems, namely the efficient basic network, intelligent coordinated transport, secure data sharing and information, integrated hub layout, systematic transport organization, unified standard specification subsystems, and clarify their technical connotations, implementation pathways and hierarchical coupling logic. The results show that the synergistic integration of a railway-trunk-based hub-and-spoke network, digital-intelligent platforms and an integrated operational model is the key to improving the connectivity efficiency of China's multimodal transport. This coupled six-subsystem technical system provides a comprehensive and operable technical reference for the high-quality and integrated development of China's multimodal transport industry.

Keywords: Multimodal transport; Hub-and-spoke network; Core common technical systems; System coupling; Implementation pathway.

1. Introduction

Driven by the "Dual Carbon" goals and supply chain resilience demands, the transportation industry is shifting toward a model where energy-efficient transport (rail, waterway) collaborates with high-speed road/air transport, creating an urgent need for systematic connectivity technologies to realize integrated multimodal operations [1]. The core of integrated transport lies in resource synergy via multimodal connections, yet existing research focuses on single dimensions (network design, route optimization) and lacks a systematic framework for cross-modal common key technologies [2]. Incomplete analysis of transport organization and hub layout has led to severe fragmentation in China's multimodal system at the facility, standard, information, and organizational levels, hampering the improvement of operational efficiency and the realization of economies of scale [3].

Internationally, internationally, multimodal transport research has achieved fruitful results with the deep integration of digital technology and transportation engineering [4]. The hub-and-spoke network, as a classic infrastructure layout model, has been continuously optimized and applied in the European Union's Trans-European Transport Network (TEN-T) and the United States' intermodal hub system, with relevant studies mostly focusing on network topology optimization and route efficiency improvement [5]. Meanwhile, cutting-edge research in developed countries has explored the application of digital twins, blockchain, and the Internet of Things (IoT) in multimodal data sharing and standard unification, but such studies are mostly limited to the technical optimization of a single link (e.g., port transshipment, trunk transport) and lack a holistic and coupled technical system framework covering infrastructure, equipment, data, organization, and standards.

In addition, existing international research on multimodal

transport connectivity is mostly based on the institutional and technical background of developed countries, and there is a lack of targeted research frameworks for the typical pain points of fragmentation in developing countries represented by China. This global research gap makes it necessary to construct a targeted and systematic technical framework combining international advanced experience with China's actual development characteristics, which constitutes the core research motivation of this paper. As a classic international multimodal infrastructure layout model, the hub-and-spoke network still provides an important reference for China [6].

This paper takes big data, cloud computing, and intelligent equipment as core underlying technologies, improves technical systems for transport organization and hub layout, clarifies the functional boundaries, coupling relationships, and implementation pathways of six major systems, and integrates international cutting-edge experience in multimodal digitalization and standardization. It constructs a reusable top-level connectivity technology framework to tackle China's multimodal "connectivity" pain points and provide technical support for industrial integrated development, and further supplements the global research on the systematic integration of multimodal transport technical systems.

2. Key Technologies and System Framework for Multimodal Transport

2.1. High-Efficiency Basic Network Technical System

As the core physical infrastructure of the six technical subsystems, the High-Efficiency Basic Network Technical System leverages advanced information technologies, smart devices, and intelligent logistics terminals to construct a Single-Network for infrastructure interconnection and a

Single-Cloud for cross-modal information exchange in multimodal transport [7]. Based on the three-dimensional transportation network integrating rail, road, waterway, and air transport resources, this system realizes seamless interconnection and real-time data sharing among cross-modal network nodes through digital and intelligent information technologies [8].

Smart devices are responsible for the full-process data collection, secure transmission, and instruction execution of multimodal transport links, and provide technical support for the automated operation and intelligent scheduling of logistics terminals. Moreover, the intelligent operation and management system built on this foundational network realizes the dynamic allocation of transport resources and coordinated scheduling of cross-modal routes according to real-time transport demand and node operation status. A comprehensive and interconnected basic network eliminates information barriers between different transport modes and operation entities, effectively improves the utilization efficiency of multimodal transport infrastructure, and lays a solid physical and technical foundation for the construction of a container-centered multimodal transport system.

2.2. Intelligent Coordinated Transport Equipment System

As the core hardware infrastructure of the six technical subsystems, the Intelligent Coordinated Transport Equipment System provides professional adaptive technical equipment for efficient and seamless cross-stage multimodal transport operations, and its intelligent application level directly determines the overall operational efficiency and cross-modal connection quality of the multimodal transport chain. By adopting specialized container transport equipment (35-tonne open-top containers, 20-foot tank containers), the system achieves optimal container-vehicle capacity matching, and flexibly adapts to different operational scenarios via coordinated scheduling of transshipment nodes and trunk routes.

Unmanned aerial vehicles (UAVs) and smart heavy-duty trucks enable autonomous cargo transshipment and terminal distribution, greatly reducing manual reliance in middle and last-mile links [9]; advanced intelligent loading and unloading equipment (straddle carriers, new-generation gantry cranes) improves transshipment hub efficiency through rational equipment and human resource coordination. In addition, full-process end-to-end operation monitoring and BDS (BeiDou Navigation Satellite System) positioning ensure the intelligent, safe, and on-time operation of transport trunks. Furthermore, the standardized design of all transport equipment is fully aligned with international container multimodal transport technical requirements, which realizes cross-mode equipment compatibility in China and provides a reliable equipment foundation for smooth cross-border container multimodal transport.

2.3. Secure Data Sharing and Information System

As the core data and information infrastructure for end-to-end multimodal transport operations, the Secure Data Sharing and Information Integration System covers the full process of cargo dispatch, trunk transport, transshipment, and delivery via a unified integrated information platform, and provides data-driven decision support for the coordinated operation of the six technical subsystems [10]. It collects multi-source

heterogeneous multimodal transport data through RFID technology, environmental sensors, and BDS positioning, realizing automatic container identification, real-time transport environment monitoring, and precise dynamic tracking of vehicles and cargoes.

Massive multi-source data is deeply mined, standardized stored, and cross-enterprise efficiently exchanged via big data analytics and EDI (Electronic Data Interchange) technology, fundamentally breaking information silos between different transport modes and entities [11]. Whole lifecycle data security is ensured by multi-level authentication, authority management, and encrypted transmission; the integration of cloud computing, blockchain, and big data technologies also enables secure credible cross-domain data sharing, forming an integrated data flow from collection, transmission, and processing to application [12]. As the core data link for transport organization and hub layout coordination, the system aligns its data exchange standards with international multimodal digital platforms, providing a standardized data foundation for efficient domestic and cross-border multimodal transport interconnection.

2.4. Integrated Hub Layout Technical System

As the dynamic operational core of the six multimodal transport technical subsystems, the Integrated Hub Layout Technical System is supported by the basic network and intelligent transport equipment, and driven by real-time data from the information integration system, advancing the transformation of multimodal operations from segmented management to integrated coordination. It is the core guarantee for full-chain operational synergy and single document system implementation, with core objectives of accelerating trunk transport, improving short-haul feeder capacity, refining cargo resource organization, and diversifying operational models.

Trunk transport relies on railway-based hub-and-spoke networks for scheduled train operations; BDS positioning ensures rail-water trunk punctuality and optimizes air-rail/air-water route coordination. Synchronized transshipment technology enables seamless container transshipment in intermediate links, with intelligent loading and unloading equipment realizing real-time coordination between operations and logistics scheduling. For last-mile feeder services, autonomous equipment integrates road transport capacity via grid-based organization and dynamic route optimization, adopting "dedicated line direct connection + intra-park loop feeder" to bridge the multimodal transport last-mile gap. Cargo resource organization achieves precise cargo-capacity matching through multi-source data analysis, promoting door-to-door multimodal transport with full-process end-to-end tracking supported by the single document system. Customized models (rail-water, road-rail, air-land, cross-border) are designed based on cargo characteristics, with specialized solutions for cold chain and hazardous chemical transport; cross-border operations comply with the International Convention on Multimodal Transport, providing solid organizational guarantees for multimodal transport cost reduction and efficiency enhancement.

2.5. Coupling Relationships Among the Six Major Technical Systems

The six multimodal transport technical subsystems form an organic, mutually supportive integrated whole, featuring a hierarchical coupling relationship of Physical Infrastructure -

Hardware Support - Data Core - Operational Organization - Standardization Assurance. This hierarchy achieves end-to-end multimodal transport integration through cross-system data interoperability and dynamic resource coordination [13].

The physical infrastructure layer (Efficient Basic Network, Integrated Hub Layout) builds the hub-and-spoke network and provides a physical operational environment for all subsystems. The hardware support layer (Intelligent Coordinated Transport Equipment) supplies professional intelligent equipment for all operational stages, with its real-time data serving as the core source for the information integration system. The data core layer (Secure Data Sharing and Information Integration) acts as the overall "nerve center", offering real-time data-driven support for transport organization and hub layout optimization. The operational organization layer, built on the above three layers, realizes full-chain dynamic organization and resource allocation via hub layout and transport organization synergy. The standardization assurance layer (Unified Standard and Specification) formulates unified cross-system standards, eliminating cross-mode and cross-entity barriers, ensuring interoperability, and aligning with international standards to support cross-border transport [14]. Collectively, the six subsystems follow the operational logic: layout defines framework, equipment provides support, data drives operations, organization boosts efficiency, standards ensures coordination, strongly underpinning high-quality integrated development of multimodal transport [15].

3. A Standardized Technical Framework with Consistent Metrics

The Unified Standard and Specification Technical System is the standardization core of the six multimodal transport technical subsystems, underpinning their systematic integration and coordinated operation. This chapter focuses on the overall design of the standard specification system, digital standard platform development, and international alignment and implementation supervision of standards, clarifying the standardized implementation basis and path for the six-domain technical framework, and laying a solid normative foundation for the integrated development of China's multimodal transport.

3.1. Overall Design of the Standard and Specification Technical System

Formulated based on the International Convention on Multimodal Transport, national policies, and multimodal hub planning, the Unified Standard and Specification Technical System balances domestic standardization advancement and international alignment. Aligned with the ISO-centered international standard system, it builds a three-dimensional implementation system covering standard platform digitalization, international standard alignment, and full-process supervision. The system clarifies the technical boundaries and standard unification requirements of each subsystem, providing institutional and normative rules for the integration and interoperability of the six subsystems, and for the cross-border application of China's multimodal transport technology system.

3.2. Development of the Digital Platform for Standards and Specifications

A unified domestic digital platform for multimodal

transport standards is built based on six standard categories, enabling centralized management, dynamic update, and efficient sharing of standard resources. Terminology and basic standards unify professional terms, eliminating conceptual ambiguities in cross-mode communication; facility and equipment standards specify technical parameters such as container dimensions and hub indicators, aligning with ISO standards for international compatibility; loading, unloading, and transport standards regulate cross-modal transshipment processes, reducing operational losses and risks; information and documentation standards unify electronic document formats and data interfaces, supporting the single document system; management and evaluation standards establish quantifiable operational, safety, and environmental indicators, boosting industrial standardized development; product classification and naming standards unify cargo codes and rules, improving cargo resource organization efficiency.

3.3. International Alignment and Implementation Supervision of Standards

A "unified domestically and aligned internationally" standard system is constructed by integrating ISO/TC 104, the International Convention on Multimodal Transport, and EU coordination experience with China's national GB/T standards and industry norms for rail, road, waterway, and air transport, eliminating cross-mode technical and regulatory barriers. The system supports China's participation in international standard formulation, with targeted technical solutions proposed to international organizations based on China's multimodal transport and Belt and Road practice, enhancing China's discourse power in global standardization.

A four-dimensional supervision system (facility, service, management, information) is established: facility supervision verifies hub, terminal, and equipment compliance; service supervision quantifies transport timeliness and customer response performance; management supervision inspects safety system and emergency plan implementation; information supervision ensures uniformity of electronic documents and data interfaces. A dynamic feedback mechanism is also set up, transmitting supervision results and industry demands to standard-setting institutions to drive iterative optimization of the multimodal transport standard system.

4. Conclusion

Based on the development status of China's multimodal transport, this study addresses the incomplete modular decomposition of transport organization and hub layout in existing research and systematically reconstructs the methodology and implementation pathways for multimodal transport connectivity. A container-centered six-domain core common technical system framework is established, with the hierarchical coupling logic of Physical Infrastructure - Hardware Support - Data Core - Operational Organization - Standardization Assurance clarified in depth. This research represents an application and in-depth development of integrated transport connectivity theory, which integrates international classical theories with cutting-edge practical experience, thus improving the international compatibility and practical applicability of the research results.

Three key conclusions are drawn. First, a reusable top-level Six-Domain Integration framework is proposed, with six

mutually coupled technical subsystems established and a three-tier Structure-Data-Organization mapping relationship formed, which addresses the research limitation of incomplete decomposition of transport organization and hub layout systems. Second, a railway-trunk-based multi-hub hub-and-spoke pattern is proposed, featuring dedicated lines/highways as supporting lines and ports/airports/railway terminals for synergistic development. Relying on the physical construction of basic networks and hub layouts, dynamic operation of transport organization systems, and data-driven operation of information systems, this pattern enables synchronous formation and continuous optimization of the "trunk–short-haul feeder–transshipment" system, effectively improving multimodal transport connectivity efficiency with internationally aligned implementation pathways. Third, the in-depth integration of the six technical subsystems is the core key to the high-quality integrated development of multimodal transport.

Only by realizing overall standardization through a unified standard and specification system and promoting the coordinated adaptation of all subsystems can China fundamentally solve the core challenges of infrastructure fragmentation, non-unified standards, and information silos in multimodal transport. The six-domain technical framework and implementation pathways proposed in this paper provide direct and operable technical references for China's multimodal transport infrastructure construction, technical system upgrading, and operational model optimization. Future research can focus on the quantitative evaluation and empirical case analysis of this framework, with typical multimodal transport hubs selected for empirical verification. The framework and pathway content can be further refined based on the practical development of regional multimodal transport in China, so as to continuously enhance the practicality and applicability of the research results and provide a Chinese solution for the global integrated development of multimodal transport.

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