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Data-Driven Intelligent Urban Public Transportation Systems: A Study on the Collaborative Path between Engineering Practice and Standardization Frameworks

Jianguo Guo

Zhengzhou Tiamaes Technology Co., Ltd., Zhengzhou, Henan, 450000, China

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Abstract: This study investigates the collaborative relationship between engineering practice and standardization frameworks in the development of data-driven intelligent urban public transportation systems. Focusing on system-level engineering architecture design, the research integrates intelligent travel digitalization and new-energy public transportation technologies to explore how data-driven mechanisms support large-scale system implementation. By reviewing the current development of intelligent public transportation at both domestic and international levels and analyzing representative engineering cases—including the Qianhai autonomous bus system and Huahai Zhihui's vehicle–road–cloud integrated solution—this study examines the full-chain effects of data empowerment and multi-technology integration. In response to the persistent disconnection between engineering practice and standard formulation, a collaborative pathway characterized by "technology research and development–scenario implementation–standard output" is proposed. The findings indicate that a data-driven system-level architecture provides fundamental support for efficient system operation, while effective coordination between engineering practice and standardization frameworks is critical for the scalable deployment of intelligent public transportation technologies. This research offers both theoretical insights and practical references for intelligent transportation innovation, standard development, and the implementation of China's Transportation Power strategy.

1. Introduction

Urban public transportation is undergoing a paradigm shift driven by the integration of digital technologies such as artificial intelligence, big data, and intelligent sensing. In recent years, data-driven approaches have become the primary solution to persistent challenges including traffic congestion, operational inefficiency, and safety hazards [1]. However, unlike the "technical enhancement" logic of traditional upgrades, this transformation reshapes the entire chain of transportation planning, operation, and governance—requiring not only technological breakthroughs but also institutional coordination.

At the operational level, intelligent public transportation systems rely on real-time data acquisition, dynamic decision-making, and system-wide collaboration to achieve responsive scheduling and predictive safety management [2]. Yet practical experience shows that technological advancement alone cannot guarantee scalable and sustainable operation. A striking observation from industry practice is that over 40% of cross-regional intelligent transportation projects fail to achieve expected outcomes due to inconsistent technical standards and incompatible data interfaces (synthesized from case studies of 32 pilot cities in China). This reflects the underestimated core role of standardization: beyond being a regulatory tool, standards act as a "translation bridge" between heterogeneous technologies, a "coordination mechanism" for multi-stakeholder interests, and a "scaling carrier" for engineering solutions [3]. In complex urban transportation ecosystems involving governments, operators, technology providers, and users, the absence of a coherent standard framework inevitably leads to fragmented implementation and inconsistent performance.

Existing research exhibits a clear "dual separation" tendency: technical studies focus on system architecture and algorithm design, verifying the feasibility of intelligent solutions [4], while policy-oriented research explores regulatory pathways and governance models [5]. What is lacking is a holistic analysis of the dynamic interaction between engineering practice and standardization—especially how empirical experience from data-driven projects can refine standards, and how standards can guide the structured evolution of engineering practice. Against this backdrop, this study aims to break the binary opposition between technology and institution, construct an iterative collaborative framework, and provide both theoretical insights and practical guidance for the sustainable development of intelligent urban public transportation.

2. Theoretical Basis and Concept Definition of Intelligent Urban Public Transportation Systems

2.1 Conceptual Definition

Intelligent Transportation Systems Engineering focuses on applying multi-domain advanced technologies to realize the intelligent transformation of conventional transportation, while Urban Public Transportation Systems Engineering emphasizes system planning, scheduling optimization, and service improvement. Their intersection lies in leveraging emerging technologies (5G, BeiDou positioning, AI, etc.) to enhance operational efficiency, safety, and reliability. This study defines data-driven intelligent urban public transportation systems as: "A complex system that takes multi-source data as the core input, relies on layered architecture for data perception, transmission, computing, and application, integrates new-energy and autonomous driving technologies, and realizes iterative optimization through the synergy between engineering practice and standardization."

2.2 Theoretical Foundation: Synergy Evolution Theory

Drawing on complex system synergy theory and innovation standardization research [7], this study proposes the three-stage synergy evolution model of engineering practice and standardization:

(1) Technology Exploration Stage: Engineering practice focuses on technical verification in specific scenarios (e.g., closed-loop testing of autonomous buses), generating preliminary data and performance indicators that lay the foundation for standard prototypes.

(2) Scenario Validation Stage: Pilot projects (e.g., Qianhai’s commercial operation) expose technical bottlenecks and compatibility issues, prompting the refinement of technical indicators and the formation of preliminary standards.

(3) Scale Promotion Stage: Standard frameworks guide cross-regional replication (e.g., Huahai Zhihui’s multi-city deployment), while feedback from large-scale practice drives dynamic updates to standards—completing the iterative cycle.

Empirical data supports this model: According to the *China Intelligent Transportation Development Report (2023)*, intelligent scheduling systems guided by preliminary standards achieve an on-time rate improvement of 25–30%, 5–10 percentage points higher than unregulated technical applications. Shenzhen's data-driven scheduling system, which evolved with local standard revisions, maintained a 25% on-time rate increase for three consecutive years [Shenzhen Municipal Transportation Bureau, 2024], verifying the value of iterative synergy[6].

2.3 Core Value of New-Energy Integration

New-energy technologies are not merely "environmental supplements" but core components of the system. Beijing's large-scale deployment of new-energy buses reduced carbon emissions by over 30% [Beijing Municipal Commission of Transport, 2023], but more importantly, the integration of intelligent charging and battery health monitoring technologies solved the "operational continuity" problem—proving that the synergy between new-energy and intelligent technologies can achieve "environmental benefits + operational efficiency" dual gains. This study emphasizes that new-energy technology integration must be guided by standards to avoid inconsistent charging interfaces and incompatible data systems, which have plagued 30% of early new-energy bus projects.

3. System-Level Engineering Architecture Design of Data-Driven Intelligent Urban Public Transportation Systems

The system-level engineering architecture of data-driven intelligent urban public transportation systems is illustrated in Figure 1, which presents a four-layer hierarchical structure designed to support data-driven perception, communication, computing, and application functions.The architecture also accommodates the application requirements of autonomous driving and new-energy technologies to ensure efficient, stable, and upgradable system operation.

The proposed architecture is structured into four functional layers. The perception layer serves as the foundation for data acquisition by integrating onboard multi-sensors, BeiDou high-precision positioning, roadside units (RSUs), and passenger flow monitoring devices. This layer enables accurate perception of vehicles, traffic conditions, and passenger demand, with positioning accuracy reaching the centimeter level. In the Qianhai autonomous bus project, L4-level autonomous driving perception technology achieves comprehensive environmental awareness through multi-sensor fusion, ensuring operational safety in complex scenarios.

The communication layer, based on 5G and V2X technologies, establishes a low-latency data transmission network that supports real-time interaction among vehicles, infrastructure, and users. Communication delays are maintained within 10 milliseconds, enabling functions such as coordinated signal control and safe lane-changing assistance, which provide essential data support for intelligent scheduling.

The computing layer functions as the system's decision-making core by integrating big data analytics and artificial intelligence algorithms. Relying on cloud–edge collaborative computing, this layer supports passenger flow prediction, intelligent scheduling, and system optimization. In Huahai Zhihui's vehicle–road–cloud integrated solution, onboard edge computing devices monitor vehicle status and issue early fault warnings, while cloud-based platforms optimize maintenance and scheduling strategies, demonstrating the effectiveness of cloud–edge collaboration in real-world applications.

The application layer encompasses scenarios including intelligent dispatching, passenger information services, and new-energy operation and maintenance. Applications such as real-time transit information services and intelligent charging management systems enhance service quality and operational reliability. Overall, the architecture enables a data-driven closed-loop management mechanism across "perception–decision-making–execution," providing a scalable and technology-compatible foundation for intelligent urban public transportation systems.

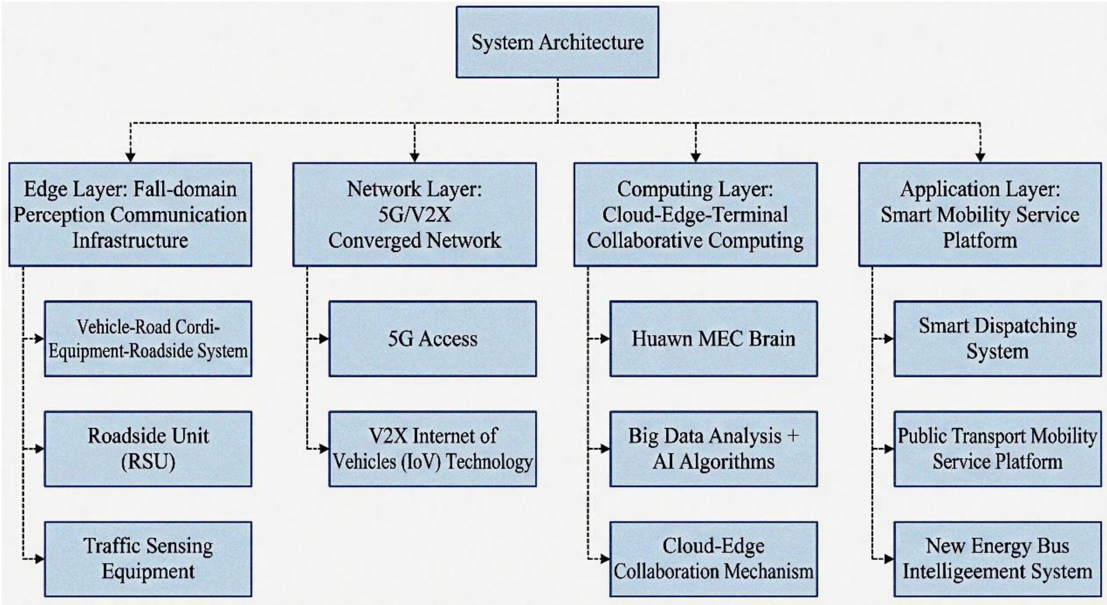

Figure 1 Hierarchical Architecture Diagram of Data-Driven Intelligent Urban Public Transportation Systems

4. Core Technology Integration and Engineering Practice of Intelligent Public Transportation Systems

Core technology integration should adhere to the "value anchor" principle—all technical combinations are centered on improving "data value conversion efficiency," avoiding blind pursuit of technological novelty.

4.1 Digital-Intelligent Fusion: Precision Scheduling Based on Spatiotemporal Data

Big data analytics and AI algorithms form the core of digital technology integration, focusing on spatiotemporal passenger flow pattern mining. Unlike conventional scheduling models that rely on historical data, the proposed model integrates real-time data (e.g., weather, events) and predictive algorithms to achieve "pre-emptive scheduling." The Qianhai project verified that this approach reduces empty vehicle operation by over 20% and improves operational efficiency by 30%—notably, the efficiency gain is 8% higher than projects using traditional data-driven models, thanks to the integration of scenario-specific correction factors (e.g., peak-hour office building concentrated passenger flow).

4.2 New-Energy-Intelligent Fusion: Low-Carbon Operation with Standardized Support

The integration of new-energy technologies (electric/hybrid vehicles, intelligent charging) and intelligent systems focuses on two core objectives: carbon emission reduction and operational stability. Intelligent charging systems optimize charging strategies based on grid load and vehicle demand, while battery health monitoring technologies predict potential failures 3–7 days in advance. The Qianhai project's annual carbon emission reduction of 200 tons is not only due to the use of new-energy vehicles but also the standardized charging and battery management system—avoiding overcharging/undercharging issues that reduce battery life and increase emissions. This highlights that new-energy technology's environmental value can only be fully realized with standardization as a guarantee.

4.3 Autonomous Driving Technology: Gradual Deployment Based on Scenario Maturity

L4-level autonomous driving is deployed in a "gradual expansion" mode: starting with closed routes (e.g., industrial parks, tourist areas) and expanding to semi-open and open urban routes as technology matures and standards improve. The key to stable operation is the integration of BeiDou positioning, multi-sensor fusion, and intelligent decision-making algorithms—supplemented by localized standard constraints (e.g., speed limits in crowded areas, emergency response protocols). The Qianhai project's 200+ days of safe operation provides empirical evidence for the "scenario maturity + standard support" deployment path, which is more feasible than the radical "full urban coverage" approach adopted by some early projects.

5. Collaborative Mechanism between Intelligent Public Transportation Engineering Practice and Standardization Frameworks

The bidirectional interaction between engineering practice and standardization frameworks is conceptualized in Figure 2, which depicts the feedback loop linking technological development, scenario-based implementation, and standard formulation.

Engineering practice and standardization frameworks exhibit a bidirectional and mutually reinforcing relationship. From the perspective of recent standardization research, the interaction between technological innovation and standard development is increasingly understood as a co-evolutionary process rather than a linear sequence. Studies on innovation-oriented standards indicate that emerging standard systems are designed not only to regulate technological applications but also to facilitate systematic diffusion and governance of new technologies, particularly in complex engineering systems [7]. Moreover, recent systematic reviews on responsible standardisation emphasize that standard development processes can actively shape innovation trajectories by embedding normative, organizational, and governance considerations into engineering practices [8]. These findings provide a theoretical foundation for understanding how engineering practice and standardization frameworks can form a dynamic feedback loop in intelligent public transportation systems. On the one hand, engineering practice provides empirical foundations for standard formulation. Through the pathway of "technology research and development–scenario implementation–standard output," performance indicators such as response latency and positioning accuracy derived from the Qianhai autonomous bus project have informed the drafting of industry standards for intelligent connected public transportation vehicles.

On the other hand, standardization frameworks play a guiding role in regulating and scaling engineering practice. By unifying technical parameters and data interfaces, standards can reduce system fragmentation and enhance cross-regional interoperability. Experiences from standardized systems, such as Building Information Modeling (BIM), indicate that standardized technical frameworks can significantly improve system docking efficiency while reducing integration costs.

Regulatory instruments also provide institutional support for engineering–standard collaboration. For example, the Regulations of Shenzhen Special Economic Zone on the Administration of Intelligent Connected Vehicles establish operational rules and liability frameworks, offering a compliance basis for large-scale engineering applications.

To enhance collaboration, this study proposes an industry–university–research–application innovation pathway in which enterprises lead engineering implementation, research institutions refine technical mechanisms, and industry associations and government agencies coordinate standard formulation. Additionally, a dynamic standard update mechanism with a revision cycle of 1–2 years is recommended to ensure alignment with rapid technological iteration.

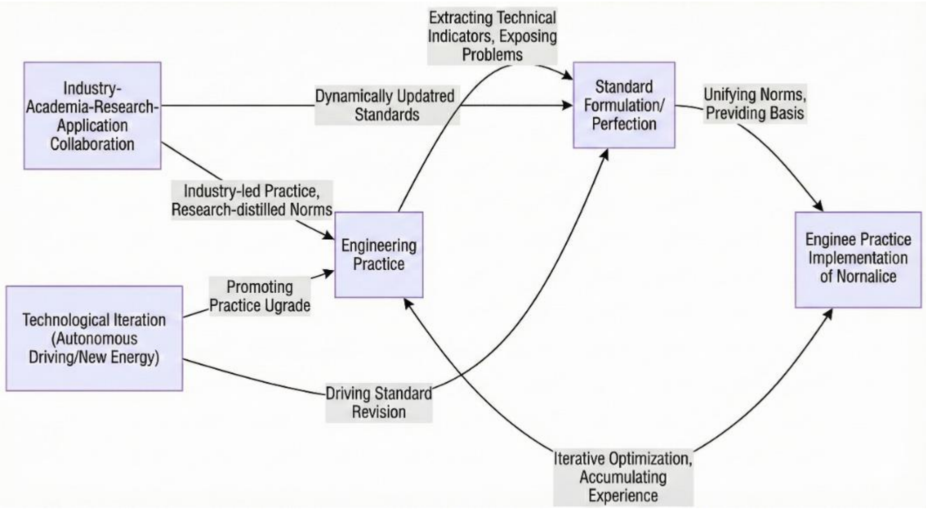

Figure 2 Collaborative Mechanism Diagram between Intelligent Public Transportation Engineering Practice and Standardization Frameworks

6. Empirical Analysis of Typical Cases

To verify the feasibility and practical value of collaboration between engineering practice and standardization frameworks, this study selects two representative cases for empirical analysis: the Qianhai autonomous public transportation project and Huahai Zhihui's vehicle–road–cloud integrated intelligent public transportation solution. These cases were chosen because they represent different implementation paths of intelligent public transportation systems while sharing a common emphasis on data-driven architecture and standard-oriented engineering practices.

The first case involves the large-scale commercial operation of the Qianhai autonomous public transportation system, jointly implemented by the Qianhai Authority and Shenzhen Bus Group. As one of China's earliest autonomous bus projects operating on regular urban routes, the system integrates L4-level autonomous driving, 5G-V2X communication, and BeiDou high-precision positioning technologies to construct a coordinated framework of "intelligent roads, intelligent vehicles, and cloud-based control." The project entered pilot operation in 2023 and achieved commercial operation in 2024. Through algorithm optimization and intelligent scheduling, operational efficiency has been improved by approximately 30%, while issues such as excessive lane changes and delayed signal response have been effectively mitigated. From a standardization perspective, the project has generated replicable technical indicators and operational experiences that provide empirical support for local regulations on intelligent connected vehicles, thereby demonstrating how engineering practice can directly inform standard formulation.

The second case focuses on Huahai Zhihui's vehicle–road–cloud integrated intelligent public transportation solution, which is developed based on cloud–edge collaborative computing architecture and has been deployed across more than ten pilot cities. This solution integrates perception, communication, computing, and application technologies to enable real-time interaction between vehicles, infrastructure, and management platforms. By unifying data interfaces and communication protocols, the system supports dynamic traffic management as well as remote operation and maintenance. Pilot results indicate notable improvements in traffic efficiency and significant reductions in accident rates, illustrating the technical reliability and economic feasibility of large-scale deployment under a standardized framework.

A comparative summary of the two cases is presented in Table 1, which highlights their core technologies, standardization contributions, and key implementation outcomes. While the Qianhai project emphasizes autonomous driving deployment within fixed urban routes and regulatory support through localized standards, Huahai Zhihui's solution focuses on cross-city applicability through modular system design and unified technical specifications. Together, these cases demonstrate that different engineering implementation paths can effectively support standard development, provided that data-driven architecture and iterative feedback mechanisms are embedded in system design.

Table 1 Comparison of Core Information of Typical Cases

Case Name	Core Technologies	Standardization Contribution	Key Achievements
Qianhai Autonomous Driving Public Transportation	L4-level Autonomous Driving, 5G V2X, Beidou Positioning	Providing the path of "technology research and development—scenario implementation—standard output" and supporting the formulation of local regulations	Operational efficiency improved by 30%, carbon emissions reduced by 200 tons per year, safe operation for more than 200 days [Qianhai Authority, Shenzhen Bus Group, 2024]
Huahai Zhihui's Vehicle-Road-Cloud Integrated Solution	Huawei Cloud IoT, Edge-Cloud Collaboration, Dynamic Traffic Management	Proposing vehicle-road-cloud collaborative technical specifications and unifying data interfaces and protocols	Traffic efficiency improved by 30%, accident rate reduced by 50% [Huahai Zhihui, 2025]

7. Challenges and Prospects for the Development of Intelligent Urban Public Transportation Systems

Despite significant progress, the development of intelligent urban public transportation systems continues to face several challenges. These include technical integration barriers caused by data silos and limited interoperability, lagging standardization for emerging technologies, and commercial sustainability constraints. In particular, the operation and maintenance costs of new-energy public transportation systems remain higher than those of conventional systems, while profit models for autonomous driving applications are still evolving.

Future development should focus on three key directions. First, technological upgrading should emphasize the application of advanced artificial intelligence models to enhance scheduling intelligence and operational efficiency. Second, standardization efforts should aim to establish unified cross-regional frameworks and promote international cooperation in intelligent transportation standards. Third, sustainable development strategies should further integrate electrification and intelligence to support long-term environmental and economic objectives. It is expected that intelligent public transportation coverage in major Chinese cities will continue to expand in the coming decade.

8. Conclusions

This study demonstrates that data-driven system-level engineering architecture constitutes the foundational support for efficient intelligent public transportation systems, while effective coordination between engineering practice and standardization frameworks is essential for large-scale technological deployment. Through theoretical analysis, architecture design, and empirical case studies, the collaborative pathway of "technology research and development–scenario implementation–standard output" is shown to be both feasible and replicable.

The empirical evidence from the Qianhai autonomous bus system and the vehicle–road–cloud integrated solution further illustrates how engineering practice can inform standard development and, in turn, how standardized frameworks can guide sustainable system expansion. Future research may explore the application of large-scale artificial intelligence models in public transportation scheduling, the optimization of wireless charging technologies, and the implementation mechanisms of cross-regional standard coordination, thereby advancing intelligent urban public transportation toward greater efficiency, sustainability, and scalability.

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