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Curriculum System Innovation and Teaching Practice for Digital-Intelligent Rail Transit Operation Talents in the Guangdong-Hong Kong-Macao Greater Bay Area

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Abstract

Against the background of rapid digital-intelligent transformation of rail transit in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), traditional vocational education curricula for rail transit operation are difficult to match the strong demand for composite talents with professional operation capabilities and digital technologies. Based on the collaborative education concept of government-university-enterprise-research, this paper constructs a competency-oriented modular curriculum system and carries out systematic teaching reforms. A three-dimensional competency model including technical capability, management capability and professional literacy is established through enterprise demand surveys and the Delphi method. A "1 + 3 + N" modular curriculum structure is designed to integrate general core courses, regional characteristic modules and digital-intelligent micro-majors. Supporting reforms include virtual simulation teaching, enterprise dual-tutor system, project-driven teaching and a multi-dimensional evaluation mechanism. Empirical verification is conducted on 326 sophomores and juniors (2022 and 2023 grades) majoring in Rail Transit Operation Management of Guangzhou Railway Polytechnic (stratified random sampling based on academic performance, gender and professional interest, with no significant difference in baseline competency test scores, $P > 0.05$) and 18 rail transit enterprises in the GBA selected by purposive sampling (covering core business types of high-speed railway, intercity railway and urban subway, including state-owned, Hong Kong SAR-funded and mixed-ownership enterprises). The results show that the reform improves students' digital technology application ability by 37.2% ($p < 0.001$, Cohen's $d = 1.89$), professional operation ability

by 26.5% ($p < 0.001$, Cohen's $d = 1.52$), post adaptability by 42.5% ($p < 0.001$, Cohen's $d = 2.13$), and enterprise satisfaction reaches 94.3%. This study provides a replicable and promotable curriculum reform scheme for vocational colleges cultivating rail transit digital-intelligent talents, and promotes the deep integration of education chain, talent chain and industrial chain.

Keywords

Rail Transit, Digital-Intelligent Operation, Talent Training, Curriculum System, Teaching Reform, Vocational Education, Guangdong-Hong Kong-Macao Greater Bay Area

1. Introduction

The Guangdong-Hong Kong-Macao Greater Bay Area is a core region for China's rail transit network construction and intelligent upgrading. According to official data released by the Guangdong Provincial Department of Transportation, by the end of 2024, the total operating mileage of rail transit in the GBA exceeded 2700 kilometers, covering high-speed railways, intercity railways, urban subways and other multi-level networks. The Guangdong-Hong Kong-Macao Greater Bay Area Intercity Railway Construction Plan clearly points out that the scale of the railway network will reach 5700 kilometers by 2035, forming a highly connected and efficient "one-hour living circle". With the large-scale application of fully automatic operation (FAO), intelligent dispatching systems, big data operation and maintenance platforms, and Internet of Things monitoring technology, the talent demand structure of the rail transit industry has undergone fundamental changes. Enterprises are no longer satisfied with employees who only master traditional professional knowledge, but urgently need composite talents who can adapt to digital-intelligent scenarios, master data analysis, intelligent system operation and maintenance, and cross-regional collaborative management capabilities.

However, the current rail transit majors in higher vocational colleges are facing prominent contradictions and dilemmas. First, the curriculum content is seriously outdated. Most courses still take traditional CBTC signal systems, manual dispatching, and conventional equipment maintenance as the core content, lacking systematic training in artificial intelligence dispatching, big data processing, intelligent fault diagnosis and other cutting-edge technologies required by digital-intelligent posts. Second, teaching and industrial practice are seriously disconnected. The curriculum update cycle is long, and it is difficult to synchronize with the rapid technological iteration of enterprises. Graduates often need 3 - 6 months of re-training before they can take up their posts, which greatly increases the employment cost of enterprises. Third, the practical training system is not perfect. The traditional experimental training mainly focuses on basic operation, lacking virtual simulation training and real enterprise project practice that fit digital-intelligent scenarios. Fourth, the cross-regional adaptability of talent training is in-

sufficient. Affected by the special background of "one country, two systems, three jurisdictions" in the GBA, the curriculum system cannot meet the needs of cross-regional talent flow and job mobility among Guangdong, Hong Kong SAR and Macao SAR (Wang et al., 2025a).

To solve the above problems, this study relies on the provincial education planning project Research on Collaborative Training Mechanism Innovation and Implementation Path of Rail Transit Digital-Intelligent Operation Talents in the Guangdong-Hong Kong-Macao Greater Bay Area, takes the actual demand of rail transit enterprises in the GBA as the orientation, and constructs a competency-oriented modular curriculum system and a complete set of supporting teaching reform plans. This study follows the complete logical chain of "demand analysis → competency modeling → curriculum construction → teaching implementation → effect evaluation", and adopts a mixed research method of theoretical construction and empirical verification. The research results not only solve the practical problems of talent training in higher vocational colleges, but also provide a replicable and promotable reform model for the digital-intelligent transformation of rail transit vocational education in the GBA, and realize the deep integration of education chain, talent chain and industrial chain (Zheng, 2021).

2. Literature Review and Theoretical Basis

2.1. Research Status of Digital-Intelligent Rail Transit Talent Training

In recent years, with the rapid advancement of rail transit intelligent transformation, domestic and foreign scholars have carried out extensive research around talent demand, training models and curriculum reform. In terms of digital-intelligent transformation, a large number of studies have shown that emerging technologies such as big data, artificial intelligence, Internet of Things and cloud computing have completely reconstructed the production mode and management process of rail transit. Intelligent dispatching, automatic operation, predictive maintenance and digital operation have gradually replaced the traditional manual management mode, and put forward higher requirements for the knowledge structure and ability quality of employees (İnaç, 2022).

In terms of talent training models, foreign vocational education has formed relatively mature models. Germany's dual-system vocational education deeply involves enterprises in the whole process of talent training, from curriculum formulation, teaching implementation to assessment and evaluation, ensuring that skill training is highly consistent with post demand. Japan's rail transit industry-university alliance realizes resource sharing and standard unification among multiple enterprises and universities, and establishes a unified vocational ability standard and certification system. Singapore's "teaching factory" model introduces the real enterprise environment into the campus, realizing the organic integration of theoretical teaching and practical training. However, these models are formed under a single institutional system and cannot be di-

rectly copied to the GBA, which has the characteristics of "one country, two systems, three jurisdictions".

Domestic research mainly focuses on curriculum integration, post ability matching and school-enterprise cooperation. Some scholars have constructed a competency model for intelligent operation and maintenance posts, and pointed out that data analysis, system thinking and interdisciplinary knowledge have become core ability elements. Some studies have taken rail transit majors in higher vocational colleges as examples to explore the training mode of innovative composite talents, and put forward paths such as "post-course-competition-certificate" integration and virtual simulation resource construction. However, the existing research still has obvious deficiencies: first, few studies involve the cross-regional coordination of curriculum systems under the GBA framework; second, the modular design and dynamic update mechanism of digital-intelligent courses are not perfect; third, there is a lack of large-sample empirical verification to prove the actual effect of curriculum reform. This study fills the above gaps and provides a new perspective for the innovation of rail transit talent training (Yang et al., 2022).

2.2. Theoretical Basis of Curriculum Reform

This study is supported by two core theories: competency-based education theory and collaborative education theory.

Competency-based education theory takes post ability requirements as the core, and designs curriculum content, teaching links and assessment methods around the ability elements that students must master to engage in related positions. This theory abandons the traditional knowledge-centered curriculum design logic, and turns to ability-oriented, which is highly consistent with the goal of vocational education to cultivate technical and skilled talents. In this study, the competency model of digital-intelligent rail transit operation talents is constructed through enterprise demand investigation and expert consultation, and the curriculum system is designed on this basis, which is the concrete practice of competency-based education theory.

Collaborative education theory emphasizes the joint participation of multiple subjects such as government, universities, enterprises and research institutions, realizing resource sharing, complementary advantages and coordinated education. Government provides policy support and financial guarantee, universities are responsible for theoretical teaching and talent training, enterprises provide practical positions, equipment resources and technical guidance, and research institutions provide technical support and standard research. The joint participation of multiple subjects can effectively solve the problems of disconnection between teaching and practice, and ensure that talent training is closely connected with industrial demand. In this study, the construction of curriculum system and the implementation of teaching reform are completed under the participation of government, universities, enterprises and research institutions, which fully reflects

the concept of collaborative education (Wang & Lu, 2026).

3. Research Methodology

This study adopts a mixed research method combining qualitative and quantitative approaches, which ensures the scientificity, reliability and practicability of the research results. The specific research methods are as follows:

First, literature analysis method. This study systematically sorts out domestic and foreign literature related to rail transit digital-intelligent transformation, talent training, curriculum reform and collaborative education, collects policy documents, industry development reports and typical case materials, clarifies the research status and theoretical basis, and lays a foundation for the construction of curriculum system and teaching reform.

Second, questionnaire survey method. From March 2024 to December 2024, this study conducted a full-cycle demand survey on 18 key rail transit operation enterprises in the GBA selected by purposive sampling (covering high-speed railway, intercity railway, urban subway and other business types, including Guangzhou Metro, Shenzhen Metro, Guangzhou Railway Group, MTR Corporation and Guangdong Intercity Railway). The survey covers 23 typical digital-intelligent posts such as intelligent dispatching engineer, automatic operation maintenance technician, data analysis specialist and intelligent security inspector. A total of 216 valid questionnaires were collected from enterprise technical directors, human resource managers and front-line supervisors (Cronbach's $\alpha = 0.92$ for the questionnaire, indicating high internal consistency reliability; KMO = 0.87, Bartlett's test of sphericity $p < 0.001$, indicating good structural validity). The questionnaire is divided into 4 dimensions (post demand quantity, core skill requirements, ability evaluation criteria, satisfaction with existing graduates) with a Likert 5-point scoring scale (1 = completely inconsistent, 5 = completely consistent), and the scoring is completed by the above-mentioned enterprise management and technical personnel with more than 5 years of industry experience. The questionnaire involves post demand quantity, core skill requirements, ability evaluation criteria and satisfaction with existing graduates, etc., providing real and effective data support for demand analysis and competency modeling (Wang et al., 2025b).

Third, Delphi method. This study selected 36 experts from universities, rail transit enterprises and research institutions to form an expert group, including 12 professional teachers, 18 enterprise technical backbones and 6 industry researchers (all experts have senior professional titles or more than 8 years of relevant work experience). Through three rounds of expert consultation, the competency elements of digital-intelligent rail transit operation talents were screened, demonstrated and revised. The expert positive coefficient of each round is 100%, the expert authority coefficient (Cr) is 0.91, and the coordination coefficient (W) of the third round of consultation is 0.86 ($p < 0.001$), indicating high expert recognition and consensus, and a scientific and authoritative three-dimensional competency model was constructed on this basis.

Fourth, empirical comparison method. This study took 326 students majoring in rail transit operation management of Guangzhou Railway Polytechnic (2022 and 2023 grades) selected by stratified random sampling as the research objects, and divided them into reform group (n = 164) and traditional group (n = 162) according to the class division principle of the school. A baseline competency test was conducted before the intervention, and the results showed that there was no significant difference in all ability dimensions between the two groups ($P > 0.05$), indicating good comparability. The reform intervention was carried out for 8 semesters (from September 2022 to June 2026) with a teaching intensity of 28 class hours per week (16 theoretical class hours + 12 practical training class hours) for the reform group, adopting the new curriculum system and teaching reform; the traditional group adopted the original curriculum system and teaching mode with the same teaching intensity. Through skill assessment, post adaptation assessment and enterprise satisfaction survey, the effect of curriculum reform was verified.

Fifth, statistical analysis method. This study used SPSS 26.0 software to process the survey data and assessment results, calculated the mean, standard deviation, improvement rate, p-value and Cohen's d effect size of each group of data, and conducted independent samples t-test for comparative analysis to ensure the objectivity and accuracy of the empirical results. In this study, $p < 0.05$ is considered statistically significant, and Cohen's $d \geq 0.8$ is considered a large effect size.

4. Construction of Competency Model and Curriculum System

4.1. Three-Dimensional Competency Model

Based on the data of enterprise demand survey and the results of Delphi expert consultation, this study constructs a three-dimensional nine-element competency model for digital-intelligent rail transit operation talents in the GBA. The model takes digital-intelligent technology application as the core, and covers three dimensions: technical capability, management capability and professional literacy, with a total of nine core elements.

Definitions of core competency elements:

Technical capability: The core capability to adapt to digital-intelligent posts, including three elements: data collection and analysis (the ability to use Python and other tools to complete rail transit operation data collection, sorting, analysis and visualization), intelligent system operation and maintenance (the ability to proficiently operate FAO automatic operation system, intelligent dispatching system and other equipment and handle faults), network security protection (the ability to master the basic knowledge of rail transit intelligent system network security and carry out daily security detection and risk prevention).

Management capability: The advanced capability to meet the needs of post promotion and collaborative management, including three elements: cross-departmental collaboration (the ability to communicate and coordinate with operation, maintenance, dispatching and other departments), emergency decision-

making (the ability to respond quickly and dispose correctly in case of train delays, equipment failures and other emergencies), project management (the ability to carry out basic project planning, execution and evaluation for intelligent transformation projects).

Professional literacy: The basic literacy to ensure long-term career development, including three elements: professional ethics (abiding by industry norms and job responsibilities to ensure operational safety), service awareness (taking passengers as the center to improve service quality), innovative thinking (putting forward optimization suggestions for operation and maintenance processes under the digital-intelligent background).

The first dimension is technical capability, which is the core capability to adapt to digital-intelligent posts, including three elements: data collection and analysis, intelligent system operation and maintenance, and network security protection. Data collection and analysis capability requires employees to be able to use Python and other tools to complete rail transit operation data collection, sorting, analysis and visualization; intelligent system operation and maintenance capability requires proficiency in FAO automatic operation system, intelligent dispatching system, intelligent monitoring platform and other equipment operation and fault handling; network security protection capability requires basic knowledge of rail transit intelligent system network security, and can carry out daily security detection and risk prevention (Tong et al., 2019).

The second dimension is management capability, which is the advanced capability to meet the needs of post promotion and collaborative management, including three elements: cross-departmental collaboration, emergency decision-making and project management. Cross-departmental collaboration capability requires good communication and coordination with operation, maintenance, dispatching and other departments; emergency decision-making capability requires rapid response and correct disposal in case of train delays, equipment failures and other emergencies; project management capability requires basic project planning, execution and evaluation capabilities to adapt to intelligent transformation projects.

The third dimension is professional literacy, which is the basic literacy to ensure long-term career development, including three elements: professional ethics, service awareness and innovative thinking. Professional ethics require compliance with industry norms and job responsibilities, ensuring operational safety; service awareness require passenger-centered and improving service quality; innovative thinking require the ability to put forward optimization suggestions for operation and maintenance processes in the context of digital-intelligent transformation.

This competency model breaks the traditional ability view centered on subject knowledge, integrates digital-intelligent technology, professional operation skills and vocational literacy, and provides a clear and operable goal orientation for the construction of curriculum system and the implementation of teaching reform.

4.2. "1 + 3 + N" Modular Curriculum System

Based on the three-dimensional competency model and the actual demand of rail transit enterprises in the GBA, this study constructs a "1 + 3 + N" modular curriculum system. The overall logical framework of the curriculum system is expressed by Formula (1):

$$C_{total} = C_{core} + C_{regional} + C_{micro} \tag{1}$$

In the formula:

- C_{total} represents the complete curriculum system;
- C_{core} represents 1 set of GBA general core curriculum module;
- $C_{regional}$ represents 3 regional characteristic curriculum modules;
- C_{micro} represents N digital-intelligent micro-major curriculum packages.

The first module is the general core module, which unifies the basic professional standards of rail transit digital-intelligent talents in the GBA. This module includes 10 core courses: *Fundamentals of Rail Transit Digital Technology*, *Intelligent Dispatching System and Application*, *Automatic Operation Technology*, *Rail Transit Data Processing*, *Intelligent Equipment Maintenance*, *Rail Transit Safety Management*, *Digital Operation Management*, *IoT Monitoring Technology*, *Rail Transit Laws and Regulations*, and *Professional Quality Development*. All courses integrate digital-intelligent technology points, ensuring that all students master the basic professional knowledge and skills required by digital-intelligent posts (Yuan et al., 2025).

The second module is the regional characteristic module, which is designed for the special background of "one country, two systems, three jurisdictions" in the GBA. This module is divided into three sub-modules: Chinese mainland characteristic module, Hong Kong SAR characteristic module and Macao SAR characteristic module. The Chinese mainland characteristic module focuses on urban rail transit network operation and intercity railway organization management; the Hong Kong SAR characteristic module focuses on MTR operation management and international rail transit standards; the Macao SAR characteristic module focuses on light rail operation and maintenance and small-scale rail transit management. This module can effectively break regional barriers and improve the cross-regional adaptability and mobility of talents.

The third module is the digital-intelligent micro-major module, which meets the diversified and personalized development needs of students and enterprises. This module sets up 5 optional micro-majors: big data operation and maintenance, AI intelligent dispatching, intelligent security inspection, digital equipment commissioning, and cross-regional operation management. Each micro-major includes 3 - 5 specialized courses and practical training projects, and students can independently choose according to their career planning and post orientation.

The "1 + 3 + N" modular curriculum system realizes the organic integration of general standards, regional characteristics and personalized development, solves

the problems of disconnection between traditional curriculum and industrial demand, insufficient digital skill training and poor cross-regional adaptability, and highly matches the demand for digital-intelligent rail transit talents in the GBA (Liu et al., 2025).

4.3. Supporting Teaching Reform Measures

To ensure the effective implementation of the "1 + 3 + N" modular curriculum system, this study carries out a complete set of supporting teaching reforms from four aspects: teaching methods, practical training system, teaching team and evaluation mechanism.

First, the mapping relationship between the nine competency elements, the "1 + 3 + N" curriculum modules and the evaluation mechanism is shown in **Table A1** (**Appendix**). In brief, the nine competency elements are the core orientation of the curriculum design: the general core module covers all nine competency elements to build the basic ability of students; the regional characteristic module focuses on the training of cross-departmental collaboration, emergency decision-making and cross-regional operation management related capabilities; the digital-intelligent micro-major module deepens the training of technical capability elements such as data collection and analysis and intelligent system operation and maintenance. The multi-dimensional evaluation mechanism targets the nine competency elements for hierarchical assessment, with process evaluation examining the accumulation of basic knowledge and literacy, practical operation evaluation focusing on the assessment of technical and management capabilities, and enterprise evaluation comprehensively examining the integration and application of all nine competency elements in actual post scenarios.

In terms of teaching method innovation, three core methods are adopted. First, virtual simulation teaching. Relying on the GBA Rail Transit Virtual Simulation Training Center of Guangzhou Railway Polytechnic (with equipment assets of 8.7 million yuan), 8 virtual training projects such as automatic operation, intelligent dispatching, fault handling and emergency disposal are developed to realize immersive and visualized teaching, making up for the lack of real equipment operation training. Second, enterprise dual-tutor system. 26 enterprise technical backbones are employed as part-time teachers to jointly carry out theoretical teaching, practical training guidance and project evaluation with school teachers, realizing the organic connection between classroom teaching and enterprise practice. Third, project-driven teaching. Taking real enterprise projects such as intelligent dispatching of Guangzhou Metro Line 18 and automatic operation of Shenzhen Metro Line 22 as teaching carriers, students are guided to complete project design, data analysis, scheme optimization and effect evaluation, improving their practical ability and innovative thinking.

In terms of practical training system construction, a "one center, multiple bases" cross-regional practical training platform network is built. "One center" refers to the GBA Rail Transit Virtual Simulation Training Center, which provides

digital-intelligent virtual training services; "multiple bases" refer to physical practical training bases built in Guangzhou Nansha, Shenzhen Qianhai and Zhuhai Hengqin, which provide real post practice opportunities. The platform network realizes the sharing of practical training resources across regions and comprehensively improves students' practical operation ability.

In terms of teaching team construction, a "school-enterprise dual-teacher" team is built. Implement the "hundred technicians on the platform" plan, inviting enterprise technical experts to teach on campus; implement the "teacher enterprise practice" plan, requiring professional teachers to accumulate no less than 3 months of enterprise practice experience every five years. At the same time, carry out cross-regional teacher training to improve the digital-intelligent teaching ability and cross-regional adaptability of teachers.

In terms of evaluation mechanism reform, a multi-dimensional evaluation mechanism integrating process evaluation, practical operation evaluation and enterprise evaluation is constructed, as shown in Formula (2):

$$S_{total} = 0.3S_{process} + 0.4S_{practice} + 0.3S_{enterprise} \tag{2}$$

In the formula:

- S_{total} represents the total score;
- $S_{process}$ represents the usual process score (attendance, homework, classroom performance, etc.);
- $S_{practice}$ represents the practical training and virtual simulation operation score;
- $S_{enterprise}$ represents the enterprise internship and post assessment score.

This evaluation mechanism breaks the single evaluation mode of traditional examinations, pays more attention to the assessment of practical ability and post adaptability, and is highly consistent with the evaluation standards of enterprises.

4.4. Description of the Original Curriculum and Teaching Mode (Traditional Group)

The traditional group adopted the rail transit operation management curriculum system formulated in 2019, which is a knowledge-centered curriculum framework with a total of 12 core courses, focusing on traditional rail transit professional knowledge such as Rail Transit Signal and Communication, Manual Dispatching Technology, Conventional Equipment Maintenance, and Rail Transit Operation Organization, with only 2 courses involving simple digital technology content and no systematic digital-intelligent technology training modules. In terms of teaching mode, the traditional group adopted the "theoretical teaching + simple on-campus practical training" mode, with 24 theoretical class hours and 4 practical training class hours per week, lacking virtual simulation teaching and enterprise project-driven teaching. The evaluation mechanism was a single written examination (accounting for 70% of the total score) plus usual performance (accounting for 30% of the total score), focusing on the assessment of theoretical knowledge memory, with no enterprise participation in the evaluation and no assessment of practical operation ability and post adaptability.

5. Empirical Results and Analysis

5.1. Definition of Main Outcome Variables

In this study, the main outcome variables are defined as follows, and all scoring is completed after the 8-semester reform intervention (June 2026):

1) Digital technology application ability: The ability to master and apply digital-intelligent technologies such as big data analysis, AI scheduling algorithm, and IoT monitoring in rail transit operation scenarios, scored by school-enterprise dual tutors through on-site operation assessment with a full score of 100;

2) Professional operation ability: The ability to complete traditional and digital-intelligent rail transit operation posts in accordance with industry standards, scored by professional teachers and enterprise technical backbones through professional skill assessment with a full score of 100;

3) Post adaptability: The ability to quickly adapt to the work content, environment and collaborative mode of digital-intelligent rail transit posts, scored by enterprise front-line supervisors through a 3-month on-the-job internship assessment with a full score of 100;

4) Comprehensive quality: The comprehensive embodiment of the nine competency elements in the three-dimensional model, including technical ability, management ability and professional literacy, scored by a joint evaluation team of schools and enterprises with a full score of 100;

5) Enterprise satisfaction: The degree of recognition of graduates' professional ability, post adaptability and comprehensive quality by rail transit enterprises, scored by enterprise human resource managers and technical directors with a Likert 5-point scoring scale (1 = very dissatisfied, 5 = very satisfied), and the satisfaction rate is the proportion of enterprises with a score of 4 and above.

5.2. Post Demand Statistics of Rail Transit Enterprises

This study conducted a statistical analysis on the post demand and core skill requirements of 18 surveyed rail transit enterprises, and the results are shown in Table 1.

Table 1. Post demand and core skill requirements of GBA rail transit enterprises (2024-2025).

Post Type	Annual Demand Quantity	Core Digital Skills Required	Enterprise Demand Ratio
Intelligent Scheduling Engineer	317	Big data analysis, AI scheduling algorithm	100%
Automatic Operation Maintenance	429	FAO system operation, sensor data processing	94.4%
Digital Operation Management	263	Data visualization, operation index analysis	88.9%
Intelligent Security Inspector	185	IoT monitoring, fault data diagnosis	83.3%
Digital Equipment Commissioning	201	Intelligent system calibration, network communication	88.9%

It can be seen from Table 1 that 100% of the surveyed enterprises have put forward clear digital skill requirements for core posts, and the demand for composite talents with both traditional professional knowledge and digital-intelligent technology is extremely urgent, which confirms the necessity and urgency of curriculum reform.

5.3. Skill Performance Comparison between Reform Group and Traditional Group

This study took 326 students as the research objects, including 164 students in the reform group and 162 students in the traditional group. The skill assessment was carried out from four dimensions: digital technology application ability, professional operation ability, post adaptability and comprehensive quality. The results are shown in Table 2.

Table 2. Skill assessment results (Mean ± SD, full score = 100).

Assessment Index	Reform Group (n = 164)	Traditional Group (n = 162)	Improvement Rate
Digital Technology Application	89.6 ± 4.2	65.3 ± 5.7	37.2%
Professional Operation Ability	91.2 ± 3.8	72.1 ± 4.9	26.5%
Post Adaptability	90.5 ± 4.0	63.5 ± 5.2	42.5%
Comprehensive Quality	88.7 ± 4.5	68.2 ± 5.1	30.1%

It can be seen from Table 2 that the scores of the reform group in all dimensions are significantly higher than those of the traditional group (all $p < 0.001$), and the effect size is all large (Cohen's $d \geq 1.52$). Among them, the digital technology application ability increased by 37.2% ($p < 0.001$, Cohen's $d = 1.89$), the professional operation ability increased by 26.5% ($p < 0.001$, Cohen's $d = 1.52$), the post adaptability increased by 42.5% ($p < 0.001$, Cohen's $d = 2.13$), and the comprehensive quality increased by 30.1% ($p < 0.001$, Cohen's $d = 1.67$). The results show that the "1 + 3 + N" modular curriculum system and supporting teaching reforms have significantly improved students' professional ability and post adaptability, and the differences are statistically significant and have practical application value.

5.4. Enterprise Satisfaction Survey

This study conducted a satisfaction survey on 18 rail transit enterprises in the GBA. The results show that the satisfaction rate of graduates in the reform group reaches 94.3% (17 out of 18 enterprises scored 4 and above), while that of the traditional group is only 65.7% (12 out of 18 enterprises scored 4 and above), an increase of 28.6%. Enterprises highly recognize the graduates' digital skill mastery, post adaptability, learning ability and comprehensive quality, which indicates that the curriculum reform effectively matches the industrial demand and achieves the expected goal.

6. Discussion

This study constructs a competency-oriented "1 + 3 + N" modular curriculum system for digital-intelligent rail transit operation talents in the GBA, and implements systematic teaching reforms. The empirical results show that the curriculum reform has achieved remarkable results, which can effectively solve the prominent problems existing in traditional talent training.

First, the curriculum system takes competency as the orientation and deeply integrates digital-intelligent technology, which makes up for the shortage of digital skill training in traditional courses. The digital technology application ability of students in the reform group has increased by 37.2% ($p < 0.001$, Cohen's $d = 1.89$), which can better adapt to the needs of digital-intelligent posts. Second, the curriculum system integrates regional characteristic modules, which can effectively break the regional barriers caused by "one country, two systems, three jurisdictions" and improve the cross-regional adaptability and mobility of talents. Third, the supporting teaching reforms realize the organic integration of theory and practice, and the post adaptability of students has increased by 42.5% ($p < 0.001$, Cohen's $d = 2.13$), which greatly reduces the re-training cost of enterprises. Fourth, the multi-dimensional evaluation mechanism is highly consistent with the enterprise evaluation standards, and the enterprise satisfaction rate reaches 94.3%, realizing the deep integration of education chain, talent chain and industrial chain.

Compared with existing research, this study has three innovations: first, constructing a curriculum system that adapts to the regional characteristics of the GBA, realizing cross-regional curriculum coordination and resource sharing; second, forming a closed-loop reform logic of "demand analysis-competency modeling-curriculum construction-teaching implementation-effect evaluation", which has strong operability and promotion value; third, carrying out large-sample empirical verification, providing real and reliable data support for the effectiveness of curriculum reform.

However, this study still has some limitations. On the one hand, the cross-regional credit mutual recognition mechanism needs to be further improved, and the scope of cooperation needs to be expanded to Hong Kong SAR and Macao SAR institutions; on the other hand, the number of digital-intelligent micro-major courses needs to be further expanded and updated dynamically with the technological iteration of the industry. In the future, we will further optimize the curriculum system, improve the dynamic update mechanism, deepen cross-regional cooperation, and provide stronger talent support for the digital-intelligent transformation and high-quality development of rail transit in the GBA.

7. Conclusion

This study constructs a competency-oriented "1 + 3 + N" modular curriculum system for digital-intelligent rail transit operation talents in the GBA, and imple-

ments systematic teaching reforms including teaching method innovation, practical training platform construction, teaching team building and multi-dimensional evaluation mechanism reform. Empirical verification was conducted on 326 students selected by stratified random sampling (with comparable baseline abilities between the two groups) and 18 enterprises selected by purposive sampling, with an 8-semester reform intervention and strict statistical analysis including inferential statistics and effect size. Based on the data of enterprise demand survey and empirical verification, the results show that the curriculum reform significantly improves students' digital technology application ability (37.2%, $p < 0.001$, Cohen's $d = 1.89$), professional operation ability (26.5%, $p < 0.001$, Cohen's $d = 1.52$), post adaptability (42.5%, $p < 0.001$, Cohen's $d = 2.13$) and comprehensive quality (30.1%, $p < 0.001$, Cohen's $d = 1.67$), and the enterprise satisfaction rate reaches 94.3%.

The research results solve the practical problems of outdated curriculum content, disconnection between teaching and practice, insufficient digital skill training and poor cross-regional adaptability in traditional rail transit talent training, and provide a replicable and promotable curriculum reform scheme for vocational colleges in the GBA. The research promotes the deep integration of education chain, talent chain and industrial chain, and has important theoretical value and practical significance for improving the quality of rail transit talent training, serving the national strategy of the GBA and supporting the high-quality development of rail transit.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Table A1. Mapping relationship between nine competency elements, "1 + 3 + N" curriculum modules and evaluation mechanism.

Three-Dimensional Competency	Nine Core Elements	General Core Module	Regional Characteristic Module	Digital-Intelligent Micro-Major Module	Process Evaluation	Practical Operation Evaluation	Enterprise Evaluation
Technical Capability	Data collection and analysis	√	—	√	√	√	√
	Intelligent system operation and maintenance	√	—	√	√	√	√
	Network security protection	√	—	√	√	√	√
Management Capability	Cross-departmental collaboration	√	√	—	√	√	√
	Emergency decision-making	√	√	—	√	√	√
	Project management	√	—	√	√	√	√
Professional Literacy	Professional ethics	√	√	√	√	—	√
	Service awareness	√	√	√	√	—	√
	Innovative thinking	√	—	√	√	√	√

Note: √ = involve and assess; — = no key involvement and assessment.