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How Can China's Autonomous Vehicle Companies Use Digital Empowerment to Improve Innovation Quality?—The Role of Digital Platform Capabilities and Boundary-Spanning Search

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Abstract: The acquisition, integration, and exchange of digital technologies considerably contribute to the improvement of corporate innovation quality, as autonomous vehicles are a complex amalgamation of multiple industrial chains. In order to address the intense global competition in the autonomous vehicles industry and help China's enterprises establish a prominent position in technological innovation, this study innovatively integrates the concepts of digital empowerment, digital platform capabilities, and boundary-spanning search into a cohesive framework, examines the pathways of influence, and methodically builds a multiple-chain mediation model. It employs various quantitative models, such as reliability and validity testing, confirmatory factor analysis, common method bias testing, mediation effect analysis, and robustness testing. The study focuses on over a hundred companies related to autonomous vehicles in China, employing software such as SPSS26.0, AMOS26.0, PROCESS4.0, and MPLUS8.3 to conduct this analysis. The findings indicate that digital empowerment is a critical factor in the improvement of innovation quality within autonomous vehicle companies. The relationship between digital empowerment and innovation quality is partially mediated by digital platform capabilities, and the boundary-spanning search also functions as a partial intermediary. Additionally, the quality of innovation and digital empowerment are mediated by the boundary-spanning search and the capabilities of digital platforms. The results of this study provide valuable insights on how to accurately empower the high-quality development of the autonomous vehicle sector with digital technologies, revealing new perspectives on the innovation quality enhancement pathways for autonomous vehicle companies in China, offering pivotal insights amidst the escalating competition within the global autonomous vehicle sector.

Keywords: digital empowerment; digital platform capabilities; boundary-spanning search; innovation quality; autonomous vehicle

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1. Introduction

Despite the substantial improvement in China's overall innovation capabilities in recent years, technological blockades have impeded the advancement of high-tech sectors, including semiconductors and artificial intelligence, which are essential drivers of innovation in the automotive industry. This has revealed deficiencies in China's fundamental technologies, a lack of novelty in innovation outcomes, and insufficient innovation quality, resulting in a phenomenon of "substantial growth in quantity but limping quality". This could have a significant impact on the strategic objective of "China becoming the forefront

of innovative countries by 2035" and has also become a significant impediment to the high-quality development of China's autonomous vehicle (AV) industry. This is not conducive to the long-term development of technological innovation and even affects China's long-term foothold on the circuit of the fierce global automobile industry competition. Chinese AV companies are confronting unprecedented opportunities and challenges. Currently, China is at the vanguard of the digital infrastructure construction industry, as it enters a new phase of intelligent development in transportation infrastructure. Still, the continuous evolution of the regulatory environment, intensifying market competition, and rapid technological iteration necessitate that enterprises utilize digital technology to improve the quality and competitiveness of innovation. The "empowerment effect" of emerging digital technologies on production innovation, including big data, artificial intelligence, cloud computing, and high-precision mapping, is becoming more apparent in the swiftly evolving digital age [1]. Empowerment has disrupted static organizations, requiring companies to perpetually adapt and update their development plans in response to real-time changes. This has been facilitated by a variety of emerging digital technologies. Digitalization not only facilitates a more precise comprehension of market demand changes and the introduction of new products, but it also stimulates the emergence of more innovative ideas, optimizes the innovation process, and empowers users to participate in the process. Thus, it is imperative to capitalize on digital empowerment in order to improve the innovation quality of China's autonomous vehicle enterprises at this juncture. This is not only crucial for the survival and growth of enterprises, but also for the preservation of China's competitiveness in the global autonomous driving sector.

The diverse digital technologies that are emerging in digital empowerment create the essential conditions for the heterogeneous resources that AV companies need to conduct boundary-spanning searches. External resources must be sought by companies to augment them, transcending organizational boundaries [2]. Simultaneously, they enable automotive companies to acquire multi-source heterogeneous resources and expand business boundaries by relying on external information, advanced technology, and innovative network resources [3]. They significantly improve enterprise forecasting and research and development capabilities, reduce uncertainty in the high-quality innovation process, and maximize the utility of innovation outcomes to achieve an improvement in corporate innovation quality by fully leveraging boundary-spanning search and digital platform capabilities to collect and analyze large-scale, diverse, and rapidly updating innovative data [4,5]. However, the majority of current research on innovation quality is directed toward external factors, such as financial subsidies, or internal decisions, such as R&D expenses, in order to examine the effects from a singular perspective. This emerging industry of AVs is rarely investigated. The academic community has not yet developed a systematic comprehension of the pathways and mechanisms that can be used to improve the quality of innovation in AV companies. Moreover, the boundaries and effects of digital empowerment in the context of the AV industry have not yet been investigated by scholars, despite the fact that it is a critical development trajectory of the current automotive industry. It is imperative to conduct a comprehensive examination of the inherent correlation between digital empowerment and innovation quality in the AV companies of China. Thus, the study distinguishes itself by specifically focusing on digital empowerment as an internal motivator of innovation quality, in contrast to previous research that concentrated on external factors and the quantity of innovation. It innovatively establishes a mechanism that connects the innovation quality of AV companies with digital empowerment by utilizing digital platforms and a boundary-spanning search.

This study addresses the aforementioned research gap by innovatively integrating the ideas of digital empowerment, digital platform capabilities, and boundary-spanning search

to answer the question of how digital empowerment might improve the innovation quality of AV firms in China. Drawing on resource orchestration theory and organizational search theory, this study investigates the influence of digital empowerment on innovation quality, as well as the individual and chain-mediating impacts of digital platform capabilities and the boundary-spanning search. It explains how digital empowerment effects the innovation quality of China's AV firms and examines the routes that lead to this outcome, giving a multidimensional analytical framework for understanding the dynamics of innovation in the AV industry. Furthermore, by focusing on China, the world's largest automotive market, the study discusses how AV companies in China can use digital technology to drive innovation, assisting stakeholders and managers in achieving high-quality innovation through digital empowerment, which is critical for global strategic and guiding purposes.

2. Theoretical Analysis and Research Hypothesis

Digital empowerment can improve autonomous vehicle performance and safety by boosting data-processing capabilities, strengthening machine learning algorithms, and optimizing sensor technology. This empowerment is directly related to innovation quality, as it accelerates the research and implementation of new technologies, improving the overall performance and reliability of autonomous cars. Furthermore, digital platforms and boundary-spanning search engines can promote cross-disciplinary collaboration by combining technologies from diverse fields, such as artificial intelligence, communication technology, and sensor technology. By combining data and algorithms from various partners, they collectively promote AV technology development, increase innovation diversity, and improve innovation quality. This is because they bring fresh insights and answers to critical difficulties in the field of AV. As a result, this study selects digital empowerment, digital platform capabilities, a boundary-spanning search, and innovation quality as factors and presents research hypotheses based on the theoretical analysis presented below.

2.1. Digital Empowerment and AV Companies' Innovation Quality

The rapid advancement of digital technologies, including artificial intelligence, the internet, big data, cloud computing, and blockchain, has given rise to a novel concept known as digital empowerment. The application scenarios of these technologies are constantly expanding. The process by which individuals or organizations acquire capabilities that they have never had through the application of digital technologies can be interpreted as such [6]. The process of empowerment is generally believed to encompass three main dimensions: structural empowerment, resource empowerment, and psychological empowerment, according to scholars [7,8]. In reality, the role of psychological empowerment is progressively diminished as a result of the increasing emphasis on the analytical capabilities, intelligence, and connectivity of digital resources and technologies with the emergence of the intelligent and digital era [9]. Furthermore, AV is a multifaceted industry that encompasses numerous industrial chains, necessitating the establishment of symbiotic relationships among the various entities within the industry chain. Ecological empowerment factors should be taken into account, as it is imperative to observe the interactions between corporate and cross-boundary system behaviors. Thus, this investigation maintains that digital empowerment should be primarily categorized into three dimensions in the present digital context: resource empowerment, structural empowerment, and ecological empowerment.

The objective of resource empowerment is to improve the capacity of enterprises to acquire, control, and manage resources during the integration process. In the AV industry, resource empowerment is typically demonstrated through the empowerment of digital technology and data. Through the mining and analysis of innovative data, data empowerment involves the acquisition of skills and methods that are then applied to a variety

of enterprise use scenarios. This process also improves the connectivity and perception capabilities of digital resources [10–12]. It motivates enterprises to consistently update their databases, thereby enabling them to more effectively utilize data and information throughout the entire innovation process, thereby enhancing innovation efficiency and fostering the enhancement of innovation quality. Digital structural empowerment facilitates the dissolution of boundaries between various innovation stages and the blurring of boundaries between industries, organizations, departments, and even products [13]. AV companies improve the application capabilities of digital technologies, continuously iterate on their innovative products in response to changes in the external environment, and enhance communication and cooperation between departments and organizations. This promotes the gradual improvement of the quality of innovative products and redefines the operation mode of the enterprise and its relationships with other enterprises. The AV industry is dependent on a variety of digital technologies within the "vehicle-road-cloud-network-map" to interact with the entire AV ecosystem. It is evolving gradually in response to external conditions, thereby continuously expanding the scope of application. This significantly enhances the direction and strength of interactions among multiple entities in the ecosystem [14]. The AV industry is building a stable cross-organizational, cross-industry, and cross-domain interconnected biological chain, which is supporting the development of the innovation ecosystem and promoting the evolution of the structure, function, institutions, and policies of various entities within the innovation ecosystem. This achieves the objective of ecological empowerment value creation [15]. This compels AV companies to utilize resources from the value network to update their innovative products, thereby maximizing their innovation quality. Accordingly, we draw our first hypothesis:

H_1. *Digital empowerment positively affects the innovation quality of AV companies.*

2.2. The Mediating Role of Digital Platform Capability

Digital platforms, which are currently the focal point of organizational innovation initiatives, are distinguished by their adaptability, affordability, and transparency. They are classified as digital resource platforms that offer services and resources to the industrial chain's upstream, midstream, and downstream segments, thereby fostering value creation. The capabilities of digital platforms are founded on digital platform technologies, including scalable architectures, generalized modules, and standardized interfaces. Complex and cumbersome digital information can be integrated, resources can be reasonably arranged and highly coordinated, and resources can be transformed into valuable digital resources that can help enterprises operate more efficiently by utilizing digital platforms [16–19]. AV companies no longer exclusively depend on chain-like transmission between two companies to acquire resource advantages; rather, they derive their advantages from a network collection that includes multiple entities, including suppliers, competitors, complementors, and consumers [20]. Digital empowerment is characterized by the elimination of organizational boundaries, which enables companies to schedule resources across time and space, fully utilize digital platform technologies, access a broader range of digital resources, and construct a multi-dimensional model for resource sharing, updating, and iteration among collaborative entities. AV companies can only then expedite the interconnection of resources, thereby considerably improving their resource integration and restructuring efficiency [18,21]. This enhances the organization's capacity to deploy and integrate internal and external resources through digitalization, thereby maintaining the essential resource base for organizational innovation activities. At this juncture, it is feasible to assert that the AV organization has acquired an exceptional digital platform capability [22]. Accordingly, the following hypothesis is proposed:

H_2. *Digital empowerment helps AV companies improve their digital platform capability.*

The second-order concept of digital platform capability encompasses platform integration and reconfiguration capabilities [23]. Digital empowerment not only introduces digital resources and technologies, such as the internet, artificial intelligence, cloud computing, and big data, but also establishes a digital platform for the exchange of resources and complementary advantages among various enterprise entities, thereby reducing the transaction and cooperation costs for AV companies [18]. The resource orchestration theory suggests that companies can achieve platform restructuring by fully utilizing the resources within the digital platform and effectively coordinating and establishing digital resources, fully leveraging the synergistic effect of resources, and more efficiently integrating the collected resources. This is achieved by acquiring a greater quantity and higher quality of resources than their competitors. The implementation of high-level platform integration and reconfiguration capabilities enhances the digital platform capability of AV companies. This allows enterprises to interchange real-time information and share operational information and technological innovation results, as well as reach a consensus with other entities and access data within the system. A succession of collaborative plans that promote information interaction and communication facilitate the platform. This allows enterprises to reconfigure and reconstruct the original internal resources and the external resources they have acquired, thereby fostering a more comprehensive development momentum for the company's innovative activities [24]. This, in turn, encourages the development of digital innovation activities of superior quality, thereby improving the innovation quality of AV companies. Accordingly, the following hypotheses are proposed:

H_3. *Digital platform capability helps AV companies improve their innovation quality.*

H_4. *Digital platform capability mediates the relationship between AV companies' digital empowerment and innovation quality.*

2.3. The Mediating Role of Boundary-Spanning Search

Organizational search theory is the source of the boundary-spanning search. The current internal knowledge resources of enterprises are inadequate to address the requirements for the enhancement of existing products and the exploration of new products as a result of the rapid changes in the dynamic environment in which autonomous car companies operate. Additionally, internal research is unable to accommodate the industry's extensive demands and the rapid pace of technological innovation. External knowledge resources are now a critical source for companies to conduct innovative activities. Companies can only surmount their innovation constraints by acquiring resources from external networks. Thus, it is imperative to employ a boundary-spanning search to transcend organizational boundaries, acquire external heterogeneous knowledge resources and information from the external environment, and integrate them into the company's own knowledge system, thereby obtaining a substantial amount of high-quality resource support [25–27]. Digital empowerment offers technical and resource support for the cross-boundary activities of AV companies, thereby breaking spatial barriers, establishing digital connections, expanding channels for knowledge resource exchange, reducing learning costs and the threshold for knowledge acquisition, significantly increasing communication speed, and continuously broadening the scope of communication. The company's operational processes and digital technology frameworks are improved, and the information processing and knowledge analysis capabilities of company members are enhanced, as a result of the establishment of a bridge for cooperation and communication between the company and other innovative entities [28]. This allows them to continuously enhance their sensitivity to information that can support their own innovative activities, resulting in a significant increase in boundary-spanning search capabilities. This is achieved by making reasonable use of the traceability of digital resources. Accordingly, the following hypothesis is proposed:

H_5. *Digital empowerment helps AV companies improve their boundary-spanning search.*

The organizational search theory posits that enterprises, motivated by practical issues in their development, intentionally seek information and acquire external knowledge from a variety of sources to establish a new knowledge base, thereby encouraging the initiation of innovative activities [29]. The interdisciplinary nature of knowledge resources and the rapid iteration of digital technologies have dispersed a multitude of innovative elements throughout the ecosystem, as AV is a complex industry. This is characterized by the integration of multiple disciplines and the intersection of various industrial chains. Digital empowerment not only enables the integration of digital information and technological resources, such as innovative products, external environments, and cooperative networks, which encourages enterprises to develop new innovative ideas and thinking [30], but also facilitates the exchange of information among various entities, thereby fostering collaborative innovation effects to achieve the co-creation of value [31]. Thus, the boundary-spanning search capabilities of AV enterprises are gradually enhanced. In addition, AV businesses that excel at boundary-spanning search can improve their own information channels and coding rules, use digital technologies to integrate knowledge networks and manage relationships, increase the quantity and retrieval efficiency of external information acquisition, encourage the efficient circulation and collision of knowledge resources, and so on. This leads to a surge in innovative ideas, better R&D, and higher-quality innovative products [32]. Accordingly, the following hypotheses are proposed:

H_6. *Boundary-spanning search helps AV companies improve their innovation quality.*

H_7. *Boundary-spanning search mediates the relationship between AV companies' digital empowerment and innovation quality.*

2.4. The Chain-Mediating Role of Digital Platform Capability and Boundary-Spanning Search

The information asymmetry that slows down innovation efforts in the modern day can be effectively mitigated by the broad use and adoption of digital technology. According to Sun [6], AV companies can stay up to date with the latest market dynamics, understand user demands better, easily grasp the direction of innovation, and encourage the sharing of digital resources and technical knowledge by establishing communication channels like digital information exchange platforms. In order to build effective resource combinations, conduct boundary-spanning searches for external knowledge, and fully leverage digital platform reconfiguration capabilities, AV companies can greatly reduce their platform transaction and cooperation costs, increase their profitability, and improve their risk-bearing capabilities. As a result, businesses are able to put more money into research and development (R&D), which leads to better innovations [18]. This boosts the innovation quality of AV companies and helps the industry as a whole optimize its innovation process. Also, digital technology can improve information exchange methods between companies, make networking, communication, and cooperation opportunities better for everyone, and give companies more control over their own development and resource allocation [33]. The digital platform capabilities of AV organizations are improved as a result of their optimization of the innovative production process and enhancement of their platform integration and reconfiguration skills.

In addition to facilitating the circulation and sharing of digital resources and advanced technologies, strong digital platform capabilities can also break down organizational barriers between companies and other entities in the platform. This can provide preconditions and resource channels for the boundary-spanning search, and enable them to more efficiently find external knowledge that can solve their own development bottlenecks. This enables companies to identify innovative opportunities, gradually enhance their perception

and adaptation capabilities to intricate external environments and market demands, and utilize external resource integration to reconstruct internal knowledge bases and develop their own innovation capabilities [34]. Ultimately, the innovation quality of AV companies can be continuously improved by designing and developing innovative products that can seamlessly connect with industry-leading products and generate synergistic effects. This is achieved by updating diversified digital technologies and resources to promote innovative activities. Accordingly, the following hypothesis is proposed.

H_8. *Digital platform capability and boundary-spanning search serve as links between digital empowerment and the innovation quality of AV companies.*

In order to investigate the mechanism by which digital empowerment influences the innovation quality of AV enterprises in China, this study develops an empirical research theoretical model, as shown in Figure 1. The model includes digital empowerment as the independent variable, digital platform capability and boundary-spanning search as the mediating and chain-mediating variables, and the innovation quality of Chinese AV enterprises as the dependent variable.

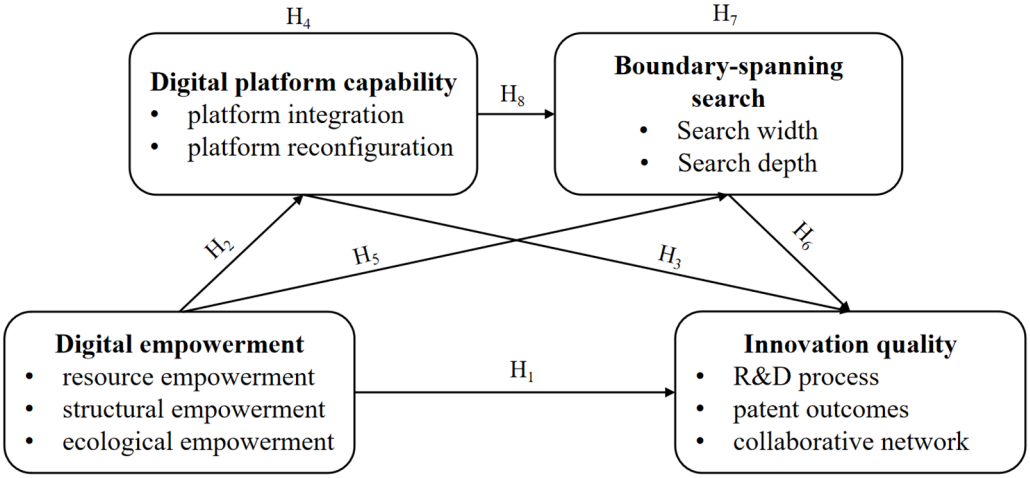

Figure 1. Conceptual model for this study.

3. Research Design

Based on the conceptual model, this study sequentially unfolds its research design through research methods, variable selection, research samples, and data collection.

3.1. Research Method

The study collects survey questionnaires from case companies to measure independent variables, mediating variables, and outcome variables, as it is challenging to obtain specific information on core constructs from corporate annual reports and publicly available secondary data. Subsequently, Statistical Package for the Social Sciences (SPSS) offers robust regression analysis capabilities, while Analysis of Moment Structures (AMOS) is particularly adept at handling complex multivariate relationships; therefore, the data collected in the study is subjected to analysis using software such as SPSS 26.0 and AMOS 26.0. In order to determine whether the variable indicators satisfy modeling standards, descriptive statistical analysis, correlation analysis, exploratory factor analysis, confirmatory factor analysis, common method bias tests, and multicollinearity tests are implemented. The causal relationships between variables are subsequently tested using multiple linear regression analysis. Due to Bootstrap being a widely applied method for testing mediation effects, the mediating functions of digital platform capabilities and the boundary-spanning search, as well as their chain-mediating effects, are verified through Bootstrap analysis

using Hayes' developed macro-PROCESS. Lastly, robustness tests are implemented to verify the research hypotheses and model of the investigation. Figure 2 shows the overall research method flowchart. In this work, different software tools were used to gradually explore the chain mediation model, examining the interactions between multiple mediators and their impact on the dependent variable. The technique enables a more in-depth and thorough understanding of the mechanisms that underpin varied interactions.

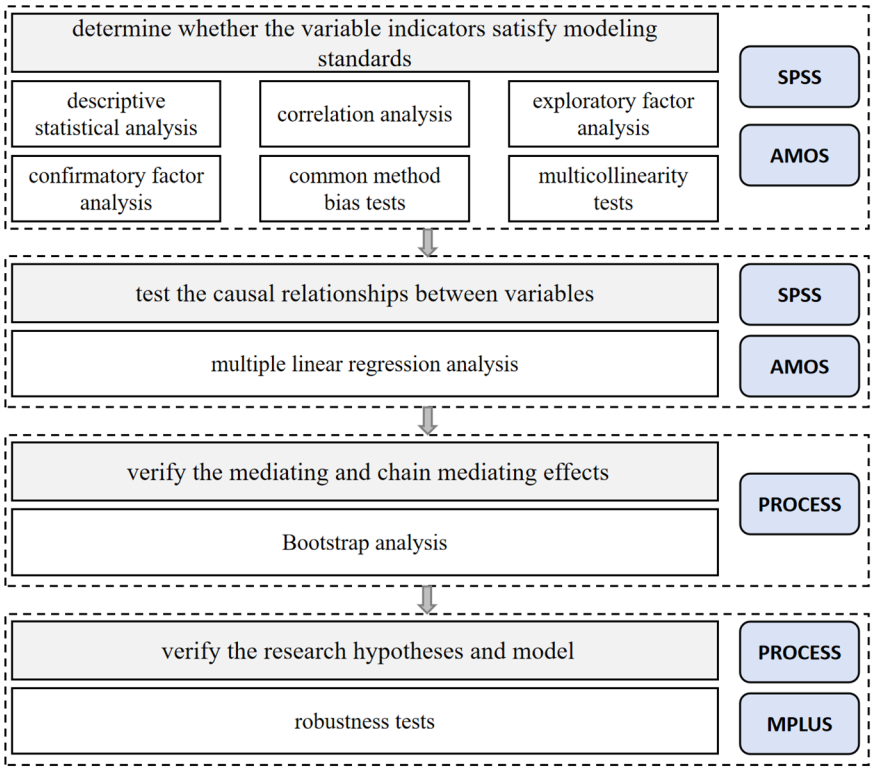

Figure 2. Research method flowchart for this study.

3.2. Variables Selection

The study selects digital empowerment as the independent variable, digital platform capabilities and cross-boundary search as the mediating and chain-mediating variables, and the innovation quality of China's AV enterprises as the dependent variable, as shown in Table 1. This is in accordance with the empirical research theoretical model. The mechanism by which digital empowerment affects the innovation quality of China's AV enterprises is investigated by Xie et al., utilizing gender, age, tenure of managers, firm age, and size as control variables [35].

We conducted back-translation, which involved translating the scales chosen for this study into Chinese, translating the Chinese scales back into English, and comparing them to the original scales to guarantee the accuracy of the research [36]. All items are evaluated using the five-point Likert scale, which ranges from 1 (completely disagree or not at all) to 5 (largely uniform or totally agree).

Our assessment of resource empowerment included four items, such as "xx company can identify big data sources that meet technical needs" ($\alpha = 0.877$), structural empowerment with four items, such as "xx company can use digital means to optimize its resource allocation and production processes" ($\alpha = 0.827$), and ecological empowerment with four items, such as "digital technology has driven the formation of mutually beneficial relationships between xx company and its partners" ($\alpha = 0.830$). Using this information, we evaluated the extent of digital empowerment by considering the current condition of the AV industry in China and utilizing Liu's [37] instruments.

Table 1. Definitions for the variables.

Variables	Title	Symbols	Description
Independent variable	Digital empowerment	DE	We evaluate the acquisition capacities of unprecedented technology in China's AV enterprises from three perspectives: resources, structure, and ecosystem.
Mediating variables	Digital platform capabilities	DPC	In terms of platform integration and reconfiguration, we assess AV companies' capacity to use digital platforms to accomplish digitally efficient operations.
	Boundary-spanning search	BS	The openness of technical innovation processes in AV businesses is investigated using two dimensions: search width and search depth.
Dependent variable	Innovation quality	IQ	The innovation level of China's AV companies is measured from three aspects: R&D process, patent outcomes, and collaborative network.
Control variables	Gender	GEN	Gender of the manager
	Age	AGE	Age of the manager
	Education	EDU	The highest educational background of the manager
	Tenure	TE	Length of tenure of the manager
	Firm age	YEAR	Number of years since the establishment of the enterprise
	Firm size	SIZE	Number of employees in the enterprise

To assess the digital platform capabilities of AV enterprises, we consult the research of Gawer [38], Helfat and Raubitschek [39], Cenamor et al. [23], and Wu et al. [40]. This assessment is based on two key components: platform integration capability and platform reconfiguration capability. In particular, we evaluate the platform integration capability using four items, including "XX company's platform can easily aggregate operational information, information regarding technological innovation results, etc., from partners' databases" ($\alpha = 0.819$), and we evaluate the platform reconfiguration capability using four items, including "XX company's platform is very easy to expand to accommodate new technological applications or functions" ($\alpha = 0.850$).

To determine a measurement scale with search width and search depth, the study selects two dimensions of search width and search depth, draws reference from Zhang and Hu [41], Guan et al. [42], and Zeng [43], and combines the actual development of Chinese AV enterprises, as per the definition of boundary-spanning search by Laursen and Salter [44]. The search depth was evaluated using four items ($\alpha = 0.918$), including "xx company has invested a lot of effort and manpower to collect potentially valuable information", and the search width was evaluated using four items ($\alpha = 0.814$), including "xx company maintains close contact with universities, research institutes, and other institutions".

This research primarily evaluates the innovation quality of Chinese AV companies from three perspectives: the R&D process, patent outcomes, and collaborative networks, in accordance with the research of Liu et al. [45], Simeth and Cincera [46], and Lu et al. [47]. In particular, the R&D process is evaluated using five items ($\alpha = 0.896$), including the following: "Company xx has fully leveraged its resource integration capabilities, strengthened connectivity and R&D, and broken-down barriers across various domains in the vehicle-road-cloud-network diagram". The patent outcomes are assessed using five items ($\alpha = 0.911$), such as "The number of citations for Company xx's patents is extremely high, indicating a high level of patent quality". Factors such as "Company xx has established a data-sharing platform with other companies in the innovation network, including maps, traffic, and vehicle data, achieving data win-win" are used to evaluate collaborative networks ($\alpha = 0.900$).

3.3. Research Samples and Data Collection

The AV industry in developed regions, including Beijing, Shanghai, Jiangsu, Zhejiang, Hubei, Chongqing, and Guangdong, has been actively involved in the construction of testing grounds, road testing, and even attempts at commercial operation, as a result of the particular emphasis on policy construction. These regions have played a good exemplary and driving role. Furthermore, the gathering of research data is facilitated by the relatively concentrated distribution of AV companies in these regions. Thus, the respondents of this study are restricted to the presidents, directors, and managers, as well as other senior and middle-level management personnel of AV enterprises in Beijing, Shanghai, Jiangsu, Zhejiang, Hubei, Chongqing, and Guangdong Province. This investigation was conducted from November 2023 to April 2024. A total of 186 companies were surveyed, and 1130 questionnaires were issued (685 offline, 445 online). A total of 984 questionnaires were collected (576 offline, 408 online), of which 697 were valid, resulting in a questionnaire validity rate of 70.8%. The plurality of management personnel were in the 31–40 age group, with a bachelor's degree or higher, and only 18.9% were below a bachelor's degree. In total, 60.8% of the respondents were male. The majority of companies were those with over 400 employees, while 54.6% were those that had been established for more than five years.

4. Results

Consistent with the research design, this study conducts an empirical analysis, and the results are presented as follows.

4.1. Descriptive Statistics Results and Correlation Coefficient Matrix

The research data do not exhibit a substantial bias, as evidenced by the moderate dispersion and reasonable range of the averages and the standard deviations of the variables in the study (Table 2). The correlation coefficients and significance between the three variables of manager education level, years since company establishment, company size and digital empowerment, digital platform capability, boundary-spanning search, and innovation quality are all relatively large, meeting the selection criteria for control variables. Consequently, the control variables in this study are these three variables. Our study also discovered that a substantial positive correlation is exhibited among independent variables, mediating variables, and dependent variables, and the correlation coefficients are all less than the square root of the AVE on the diagonal table, which indicates the scales employed in the study have relatively outstanding discriminant validity.

Table 2. Variable means, standard deviations, and correlation coefficients (n = 697).

Variables	SEX	AGE	EDU	EU	YEAR	SIZE	DE	DPC	CS	IQ
GEN	1									
AGE	−0.03	1								
EDU	0.071	−0.024	1							
TE	−0.026	−0.026	0.028	1						
YEAR	−0.06	−0.025	0.112 **	0.044	1					
SIZE	−0.119 **	0.005	0.115 **	−0.026	0.145 **	1				
DE	−0.038	0.014	0.272 **	−0.054	0.261 **	0.349 **	0.762			
DPC	−0.062	−0.033	0.201 **	−0.040	0.249 **	0.255 **	0.586 **	0.748		
BS	−0.044	−0.036	0.183 **	−0.009	0.215 **	0.286 **	0.500 **	0.543 **	0.793	
IQ	−0.042	−0.001	0.282 **	−0.02	0.305 **	0.327 **	0.632 **	0.330 **	0.595 **	0.815
AVERAGE	1.390	2.570	2.400	2.750	2.590	2.710	3.153	3.193	3.032	3.320
SD	0.488	0.878	0.950	1.050	0.966	0.865	0.853	0.889	0.953	0.901

Note: The diagonal is the square root of the AVE corresponding to the dimension. n is the sample size. ** $p < 0.01$.

4.2. Confirmatory Factor Analysis

The discriminant validity of the model factors was evaluated using AMOS 26.0 software. Table 3 shows that the four-factor model has a CMIN/DF of 2.225, which is the smallest among the other factor configurations. Conversely, the RMSEA is 0.042, the TLI is 0.930, and the CFI is 0.935, all of which are greater than 0.9. As a result, the four-factor model is the most suitable in comparison to the three-factor, two-factor, and single-factor models. The variables included in the theoretical model constructed in the study have excellent discriminant validity, and the fit of the variables meets the relevant standards.

Table 3. Confirmatory factor analysis test for discriminant validity.

	CMIN	DF	CMIN/DF	IFI	TLI	CFI	RMSEA
Four-factor model	1967.046	884	2.225	0.935	0.930	0.935	0.042
Three-factor model	2503.189	891	2.809	0.903	0.897	0.903	0.051
Two-factor model	2616.816	893	2.930	0.896	0.890	0.896	0.053
One-factor model	2647.332	894	2.961	0.895	0.888	0.894	0.053

Note: four-factor model = DE, DPC, BS, and IQ; three-factor model = DE + DPC, BS, and IQ; two-factor model = DE + DPC + BS, and IQ; one-factor model = DE + DPC + BS + IQ.

4.3. Common Method Deviation Test

In order to effectively address the common method bias issue, the study implements Harman's single-factor test [48] for principal component analysis. In Table 4, all items were extracted into 10 common factors with eigenvalues greater than 1, and the 10 factors explained 71.117% of the total variance, which is greater than 60%. This indicates that the factor extraction effect was effective. However, the maximum common factor explains 31.919% of the variables, which is less than 40%. There is no example in which a single common factor explains the majority of the variance, indicating that the sample data do not have common method bias issues.

Table 4. Total variance interpretation.

Total Variance Interpretation	Initial Eigenvalue			Sum of Squared Loadings			Sum of Squared Loadings After Rotation		
	Total	Variance%	Cumulative%	Total	Variance%	Cumulative%	Total	Variance%	Cumulative%
1	13.406	31.919	31.919	13.406	31.919	31.919	3.766	8.967	8.967
2	2.807	6.684	38.603	2.807	6.684	38.603	3.61	8.595	17.562
3	2.375	5.656	44.259	2.375	5.656	44.259	3.25	7.737	25.299
4	2.095	4.989	49.248	2.095	4.989	49.248	3.038	7.232	32.531
5	1.775	4.226	53.474	1.775	4.226	53.474	2.822	6.719	39.25
6	1.757	4.184	57.657	1.757	4.184	57.657	2.746	6.538	45.788
7	1.536	3.658	61.316	1.536	3.658	61.316	2.705	6.441	52.229
8	1.479	3.521	64.836	1.479	3.521	64.836	2.688	6.4	58.629
9	1.352	3.22	68.056	1.352	3.22	68.056	2.683	6.389	65.018
10	1.286	3.061	71.117	1.286	3.061	71.117	2.562	6.1	71.117

A Variance Inflation Factor (VIF) of less than 10 indicates that the independent variables in the model are not multicollinear. The model is deemed to lack multicollinearity when the tolerance is greater than 0.1. The results of the multicollinearity test are presented in Table 5. The results indicate that the independent variable indicators in the model satisfy the modeling standards, as all variables in the path have VIF values less than 10 and the tolerance values are all greater than 0.1.

Table 5. Multicollinearity test.

Variables	Tolerance	VIF
EDU	0.921	1.086
YEAR	0.911	1.097
SIZE	0.859	1.164
DE	0.558	1.793
DPC	0.568	1.762
CS	0.642	1.557

4.4. Hypothesis Testing

The investigation implements multiple hierarchical regression analysis. Model 5 evaluated the direct impact of digital empowerment on innovation quality. The results, as indicated in Table 6, suggest that digital empowerment has a substantial positive influence on the innovation quality of AV companies ($\beta = 0.528$, $p < 0.001$). Thus, hypothesis H_1 is supported.

Table 6. An analysis of the mediating role of digital platform capabilities in the relationship between digital empowerment and innovation quality.

Variables	Digital Platform Capabilities		Innovation Quality			
	M1	M2	M3	M4	M5	M6
Control variables						
EDU	0.154 ***	0.039	0.224 ***	0.003	0.110 ***	0.099 ***
YEAR	0.202 ***	0.099 **	0.241 ***	0.156 ***	0.139 ***	0.110 ***
SIZE	0.208 ***	0.050	0.266 ***	0.178 ***	0.110 ***	0.095 **
Independent variables						
Digital empowerment		0.532 ***			0.528 ***	0.373 ***
Intermediate variables						
Digital platform capabilities				0.496 ***		0.290 ***
R^2	0.134	0.357	0.224	0.394	0.443	0.497
ΔR^2	0.131	0.353	0.221	0.390	0.440	0.494
F	35.830	96.068	66.652	112.46	137.726	136.732
ΔF	35.830	239.751	66.652	1.821	272.587	74.358

Note: ** $p < 0.01$; *** $p < 0.001$.

4.4.1. Verifying the Mediating Role of Digital Platform Capabilities

In order to investigate the mediating effect of digital platform capabilities, the study implements hierarchical regression analysis in accordance with the mediating effect testing procedure proposed by Wen et al. [49]. Table 6 shows the regression findings. The direct effect of digital empowerment on digital platform capabilities is examined in Model 2. The results of the study indicate that digital empowerment has a substantial positive impact on digital platform capabilities ($\beta = 0.532$, $p < 0.001$). Therefore, this supports hypothesis H_2.

Model 4 applies innovation quality as the dependent variable and digital platform capability as the independent variable in its regression analysis. The findings indicate that the innovation quality of AV enterprises is significantly positively influenced by digital platform capability ($\beta = 0.496$, $p < 0.001$), and hypothesis H_3 is valid. Model 6, which incorporates the mediating variable of digital platform capabilities into Model 5, continues to demonstrate a substantial positive impact of digital empowerment on the innovation quality of AV companies ($\beta = 0.290$, $p < 0.001$). This suggests that digital platform capabilities mediate the relationship between digital empowerment and the innovation quality of AV companies, therefore supporting hypothesis H_4.

4.4.2. Verifying the Mediating Role of Boundary-Spanning Search

The mediating effect of boundary-spanning search is investigated using hierarchical regression analysis in accordance with the mediating effect testing procedure proposed by Wen et al. [49]. Table 7 shows the regression findings. Model 8 evaluates the direct impact of digital empowerment on boundary-spanning search. The results show that digital empowerment has a substantial positive influence on boundary-spanning search ($\beta = 0.424$, $p < 0.001$). This supports hypothesis H_5.

Table 7. An analysis of the mediating role of boundary-spanning search in the relationship between digital empowerment and innovation quality.

Variables	Boundary-Spanning Search		Innovation Quality			
	M7	M8	M3	M9	M5	M10
Control variables						
EDU	0.136 ***	0.045	0.224 ***	0.158 ***	0.110 ***	0.095 **
YEAR	0.164 ***	0.082 *	0.241 ***	0.161 ***	0.139 ***	0.111 ***
SIZE	0.247 ***	0.121 **	0.266 ***	0.146 ***	0.110 ***	0.068 *
Independent variables						
Digital empowerment		0.424 ***			0.528 ***	0.382 ***
Intermediate variables						
Boundary-spanning search				0.490 ***		0.343 ***
R^2	0.131	0.273	0.224	0.432	0.443	0.529
ΔR^2	0.127	0.268	0.221	0.429	0.44	0.525
F	64.825	64.825	66.652	131.712	137.726	154.975
ΔF	134.869	134.869	66.652	253.918	272.587	125.142

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Model 9 applies innovation quality as the dependent variable and boundary-spanning search as the independent variable in regression analysis. The results indicate that hypothesis H_6 is valid, and boundary-spanning search has a substantial positive effect on the innovation quality of AV enterprises ($\beta = 0.490$, $p < 0.001$). Model 10, which incorporates the mediating variable boundary-spanning search into Model 5, continues to show a substantial positive impact of digital empowerment on the innovation quality of AV companies ($\beta = 0.343$, $p < 0.001$). This suggests that boundary-spanning search mediates the relationship between digital empowerment and the innovation quality of AV companies, thereby supporting hypothesis H_7.

4.4.3. Verifying the Chain-Mediating Role of Digital Platform Capabilities and Boundary-Spanning Search

In order to investigate the chain-mediating effects of digital platform capability and boundary-spanning search, the study implemented the chain-mediating test procedure developed by Allen and Griffeth [50]. Despite the inclusion of the mediating variable digital platform capability in Model 6, digital empowerment continued to have a substantial impact on innovation quality ($\beta = 0.373$, $p < 0.001$), as shown in Table 8. This indicates that digital platform capability has a substantial impact on innovation quality ($\beta = 0.290$, $p < 0.001$). Furthermore, in Model 11, the mediating variable boundary-spanning search had a significant positive impact on innovation quality ($\beta = 0.282$, $p < 0.001$), digital platform capability had a significant positive impact on innovation quality ($\beta = 0.187$, $p < 0.001$), and digital empowerment still had a significant positive impact on innovation quality ($\beta = 0.308$, $p < 0.001$). Therefore, hypothesis H_8 is preliminarily validated, and the chain-mediating effects of digital platform capability and boundary-spanning search are preliminarily supported.

Table 8. An analysis of the chain-mediating role of digital platform capabilities and boundary-spanning search.

Variables	Innovation Quality			
	M3	M5	M6	M11
Control variables				
EDU	0.224 ***	0.110 ***	0.099 ***	0.090 **
YEAR	0.241 ***	0.139 ***	0.110 ***	0.097 ***
SIZE	0.266 ***	0.110 ***	0.095 **	0.066 *
Independent variables				
Digital empowerment		0.528 ***	0.373 ***	0.308 ***
Intermediate variables				
Digital platform capabilities			0.290 ***	0.187 ***
Boundary-spanning search				0.282 ***
R^2	0.224	0.443	0.497	0.549
ΔR^2	0.221	0.440	0.494	0.545
F	66.652	137.726	136.732	139.715
ΔF	66.652	272.587	74.358	78.223

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

4.4.4. Bootstrap Test

The study applies the macro-PROCESS developed by Hayes for Bootstrap testing (n = 5000 times) to further substantiate the mediating and chain-mediating effects, as well as to observe the final results at a 95% confidence level. Hayes Model 4 serves as the foundation for model testing when the mediation variable is incorporated into the model. Table 9 displays the total effect, direct effect, and indirect effect quantities of the Bootstrap mediating effect test model.

Table 9. Bootstrap test for mediating and chain-mediating effects.

Effect Path	Effect Value	Standard Error	95% Confidence Interval	
			Lower Limit (LLCI)	Upper Limit (ULCI)
DE→DPC→IQ				
Total	0.516	0.035	0.448	0.584
Direct	0.370	0.038	0.297	0.444
Indirect	0.145	0.021	0.105	0.188
DE→BS→IQ				
Total	0.516	0.035	0.448	0.584
Direct	0.377	0.035	0.309	0.444
Indirect	0.139	0.019	0.103	0.179
DE→DPC→BS→IQ				
Total	0.516	0.035	0.448	0.584
Direct	0.307	0.036	0.235	0.378
Indirect	0.052	0.010	0.035	0.073

The indirect effect, or mediating effect value, in the "digital empowerment→digital platform capability→innovation quality" path is 0.145, with a 95% confidence interval of 0.105 to 0.188. The direct effect path is 0.297 to 0.444, which also does not include 0, and the confidence interval does not include 0. This suggests that the mediating effect of digital platform capability is substantial and is a partial mediating effect. Consequently, hypothesis H_4 is established, as the partial mediating effect of digital platform capability between digital empowerment and AV company innovation quality is validated. Similarly, hypotheses H_7 and H_8 are also established.

4.5. Robustness Testing

4.5.1. Sub-Sample Robustness Test

The study conducted robustness tests on the theoretical research hypotheses by arbitrarily selecting 150 and 350 samples from a pool of 697, in accordance with the methodology of Liu and Kong [51]. As shown in Table 10, the regression coefficients of the direct relationships between variables did not differ in terms of significance level, with the exception of minimal differences in magnitude, regardless of whether 150 or 350 samples were randomly selected. Additionally, the confidence intervals for the individual mediating effects of digital platform capability and boundary-spanning search, as well as their chain-mediating effect, do not include zero, suggesting that all research hypotheses are once again being supported and validated. Thus, the robustness test of the sub-samples confirms the robustness of the original empirical analysis results of the study.

Table 10. Bootstrap test for mediating and chain-mediating effects (sub-sample robustness test).

Effect Path	*n* = 150				*n* = 350			
	Effect Value	**Standard Error**	**Boot LLCI**	**Boot LLCI**	**Effect Value**	**Standard Error**	**Boot LLCI**	**Boot LLCI**
DE→DPC→IQ								
Total	0.324	0.090	0.145	0.503	0.871	0.092	0.688	1.054
Direct	0.148	0.059	0.044	0.277	0.686	0.102	0.483	0.889
Indirect	0.137	0.052	0.041	0.246	0.185	0.073	0.066	0.352
DE→BS→IQ								
Total	0.324	0.090	0.145	0.503	0.871	0.092	0.688	1.054
Direct	0.197	0.084	0.032	0.363	0.698	0.105	0.489	0.906
Indirect	0.127	0.055	0.028	0.242	0.173	0.063	0.072	0.316
DE→DPC→BS→IQ								
Total	0.324	0.090	0.145	0.503	0.871	0.092	0.688	1.054
Direct	0.166	0.077	0.028	0.329	0.621	0.107	0.408	0.834
Indirect	0.118	0.050	0.026	0.224	0.249	0.091	0.107	0.467

4.5.2. Measurement Method Transformation Robustness Test

Scholars argue that research findings are regarded as robust if they remain unaltered after re-analysis using alternative validation methods, such as Bootstrap [35]. Thus, the study initially employs MPlus8.3 software for statistical analysis and subsequently employs the Bootstrap method to evaluate the effects of chain mediation and mediation. The analysis in Table 11 shows that the research hypotheses are still supported. Therefore, the robustness test of the measurement method modification confirms the robustness of the original empirical analysis results of the study.

Table 11. MPlus-based Bootstrap mediating and chain-mediating effects test.

Effect Path	Estimate	Lower 2.5%	Upper 2.5%
Direct effects	0.381	0.312	0.451
Indirect effects	0.287	0.232	0.344
DE→DPC→IQ	0.127	0.079	0.176
DE→BC→IQ	0.089	0.058	0.123
DE→DPC→BC→IQ	0.071	0.050	0.097

5. Discussion

This section integrates the aforementioned research findings to discuss the research methodology and results separately.

5.1. Discussion of Methodology

This study draws on the methods for mediation and chain-mediation models as presented by Jiang and Zheng [21], Wu et al. [40], and Xie et al. [35], and employs multiple software for validation. By combining the strengths of several approaches, this study investigates the interaction of many mediators and their impact on the dependent variable, revealing the mechanisms behind the interactions between variables in a more comprehensive and rigorous manner.

5.2. Discussion of Research Results

The results in Table 12 indicate that each of the eight hypotheses that were put forth in this investigation is supported. The study expands on the action mechanism between variables in accordance with the data analysis results to clarify the causes for the influence of the mechanism between variables.

Table 12. The results of the hypothesis test.

Hypothesis	Contents of the Hypothesis	Results
H_1	Digital empowerment positively affects the innovation quality of AV companies.	support
H_2	Digital empowerment helps AV companies improve their digital platform capability.	support
H_3	Digital platform capability helps AV companies improve their innovation quality.	support
H_4	Digital platform capability mediates the relationship between AV companies' digital empowerment and innovation quality.	support
H_5	Digital empowerment helps AV companies improve their boundary-spanning search.	support
H_6	Boundary-spanning search helps AV companies improve their innovation quality.	support
H_7	Boundary-spanning search mediates the relationship between AV companies' digital empowerment and innovation quality.	support
H_8	Digital platform capability and boundary-spanning search serve as links between digital empowerment and the innovation quality of AV companies.	support

5.2.1. Discussion of the Influence Relationship Between Digital Empowerment and Innovation Quality of AV Companies

The research determined that the quality of AV companies' innovation is more likely to improve as the level of digital empowerment increases ($\beta = 0.528$, $p < 0.001$). The integration of digital technology in the field of AVs has the potential to provide the entire industry with a greater number of state-of-the-art technological resources, thereby accelerating the process of digital innovation. In order to continuously improve the efficiency of innovative products and achieve high-quality innovation for the enterprise, each AV company can combine its own development status to apply appropriate digital technologies to innovative production activities under the innovation drive of the entire industry chain [52].

The continuous advancement and empowerment of digital technology are necessary to expedite the evolution of China's AV industry toward higher-order development. For example, the company has revolutionized a series of key leading technologies in the fields of vehicle-side BEV, automatic mapping and updating, and geographic information visualization in its innovative production activities by utilizing cutting-edge digital technologies, such as the fourth-generation PPP-RTK positioning technology. This has facilitated the high-quality development of the company's innovative activities. The study confirms that digital technology and digital infrastructure can empower the innovation process within organizations, and extends the mechanism of action to the field of AVs, assisting China's AV companies in enhancing their innovation quality. This is based on the work of Hu and Lu [53], Ghasemaghaei and Calic [54], Chen et al. [55], Liang et al. [56], and Zhao and Huang [57].

5.2.2. Discussion of the Influence Relationship of Digital Platform Capability

The research determined that the more digitally empowered AV enterprises are, the more likely they are to improve their digital platform capabilities ($\beta = 0.532$, $p < 0.001$). Initially, digital empowerment information technologies, including cloud computing and big data, provide high-quality raw materials for the development of digital platforms. To a certain extent, they have the ability to expand the production, finalized products, and service boundaries of AV companies, as well as to modify the production processes and organizational structures. Companies can optimize their structural combinations and reconfigure various elements by gradually iterating the data resources of the digital platform [58].

The study further found that the innovation quality of AV companies is more positively influenced by the level of digital platform capabilities ($\beta = 0.496$, $p < 0.001$), and the fact that digital platform capabilities mediate the relationship between digital empowerment and the innovation quality of AV companies ($\beta = 0.373$, $p < 0.001$). The digital platform can be empowered by digital resources and technologies, allowing multiple enterprise subjects in the AV industry chain to share technical information and knowledge resources. Furthermore, the digital platform enables the full flow and coupling of a variety of innovative elements throughout the industry chain development, thereby transforming the traditionally independent information silos of each enterprise into information interconnection sharing and collaborative innovation development within the entire platform ecosystem [59,60].

The digital platform includes a variety of innovative achievements and excellent development tools in the AV industry, including multiple segments of the entire chain of AV innovation production research and development, including data collection, data storage and annotation, algorithm simulation and simulation, data feedback, and operation. Companies can accelerate the pace of research and development, drive the rapid iteration of innovative technologies, and promote the high-quality development of corporate innovation activities and the early realization of large-scale landing of innovative achievements when they have a higher level of digital platform capabilities. Additionally, they can explore new cooperation models and update business models. By incorporating digital platform capabilities into the field of AVs, the study expands upon the research of Jiang et al. [61], Gong et al. [62], and Meng and Yao [63]. This confirms the importance of digital platform capabilities in the advancement of technological innovation in autonomous driving. It also confirms the substantial mediating effect of platform integration and reconfiguration capabilities in the pathway by which digital empowerment improves the quality of innovation in AVs.

5.2.3. Discussion of the Influence Relationship of Boundary-Spanning Search

The research determined that the more digitally empowered AV enterprises are, the more conducive an enterprise is to the improvement of boundary-spanning search ($\beta = 0.424$, $p < 0.001$). Digital platforms and ecosystems consolidate a diverse array of high-quality companies from the upstream, midstream, and downstream sectors of the AV industry chain. Each entity contributes distinctive and critical scarce resources. Their dynamism and openness allow companies to overcome technical barriers and resource constraints by utilizing resource aggregation effects and supply–demand matching functions to more accurately capture heterogeneous resources that solve their own dilemmas. This enables them to reorganize knowledge and reshape structures [64,65].

Simultaneously, the investigation determined that the innovation quality of AV companies is more positively influenced by the level of boundary-spanning search ($\beta = 0.490$, $p < 0.001$) and the mediating effect of boundary-spanning search on digital empowerment

($\beta = 0.382$, $p < 0.001$). A significant number of interdisciplinary innovation elements and digital technologies are dispersed throughout digital platforms and ecosystems due to the fact that autonomous driving is a complex industry that integrates multiple industry chains. Digital empowerment can help AV companies improve their boundary-spanning search capabilities over time. This can be achieved by strengthening communication and information exchange between different companies in the industry chain, learning about the research and development dynamics of competing companies, and building patent cooperation networks and communication platforms. Additionally, AV companies can increase the breadth and depth of their knowledge acquisition for the boundary-spanning search [66]. Companies that are able to search across boundaries more effectively are better able to improve the quality of their innovations as a whole. This is because these companies are able to tap into a wider variety of resources and information, including user feedback and market data, which allows them to capture market opportunities more quickly and incorporate new technologies into their innovative production processes. This also stimulates more innovation and helps AV companies develop more competitive innovative products.

Due to the fact that certain domestic car manufacturing companies are transitioning from technology and internet companies, they lack the necessary technical reserves. Therefore, they opt for collaboration with other brands across borders, sourcing parts and contract manufacturers that align with their own positioning. They then combine these components with their own-developed controllers, chips, and other products to broaden their product line and develop autonomous vehicles that offer unique advantages. Simultaneously, certain domestic automobile manufacturers will establish their own intelligent ecosystems and autonomous driving technologies, thereby establishing collaboration channels with other organizations. This will allow for the collaborative enhancement of the innovation technology ecosystem through a robust boundary-spanning search, resulting in the high-quality development of innovation production activities in AV companies. The research on boundary-spanning search is extended to the AV industry in this study, which builds upon the work of Xiao and Zhu [67], Yang et al. [68], and Jiang et al. [69]. It substantiates the significance of the boundary-spanning search during the current phase of AV development in China and shows its partial mediating role in the process by which digital empowerment improves the innovation quality of AVs.

5.2.4. Discussion of the Influence Relationship Between Digital Platform Capability and Boundary-Spanning Search Chain Mediation

The bootstrap test results of the study revealed that digital empowerment contributes to the improvement of the digital platform capabilities of enterprises, which in turn facilitates the boundary-spanning inquiry of enterprises, thereby enhancing the innovation quality of AV companies. In particular, the AV industry can reduce the issue of sluggish progress in corporate innovation activities caused by information asymmetry by empowering digital technology and knowledge resources. The establishment of digital platforms and other communication channels can allow various entities in the ecosystem to remain informed about real-time market dynamics and make opportune strategic adjustments and structural reconfiguration based on user feedback. This improves the digital platform capabilities of various enterprises, enhances knowledge sharing and complementary exchanges among AV companies, and effectively reduces the cost of information collection by leveraging strong resource integration and platform reconfiguration capabilities. It fosters the active exchange of advanced knowledge and technological resources among a variety of entities, thereby improving the capacity to search across boundaries. Ultimately, enterprises can enhance the quality of innovation outcomes by excavating, developing, utilizing, and accumulating a greater variety of knowledge resources from external sources,

augmenting the speed of integration, constructing more effective resource combinations, and refining their own innovation processes [70].

The innovation of AV companies can be facilitated by the introduction of richer, high-quality raw materials through digital empowerment methods, such as cloud computing, high-precision mapping, and model algorithms. This aids in the generation and comprehension of data scenarios, including pre-annotation and multi-modal retrieval, and promotes the enhancement of data-processing efficiency. Companies can leverage their superior digital platform capabilities to annotate external data, select and process it in accordance with their own development situation, actively participate in exchanges and sharing within the platform, and develop robust boundary-spanning search capabilities, as digital platforms are equipped with a vast array of data samples, multi-model data algorithms, and multi-perspective scenario coverage. Ultimately, they can achieve innovation quality enhancement across the entire industry chain, including single-vehicle intelligence, vehicle–road collaboration, 5G remote control, real-time digital twins, and other "vehicle-road-cloud-network-map" full-chain innovations, by utilizing diversified digital technologies and knowledge resources to drive the progress of innovation activities and assist in the continuous improvement of innovation quality in AV companies. The study integrates the current state of China's AV industry development and verifies that digital platform capabilities and boundary-spanning search play a chain-mediating role in the pathway through which digital empowerment enhances the innovation quality of China's AV enterprises, thereby expanding the scope of influence. This is based on the research of Cenamor et al. [23], Wang et al. [71], Yang et al. [72], and Jiang and Zheng [21].

The paradigm offered in this study can be useful for countries with a thriving tech sector or those aiming to stimulate innovation. Policymakers and corporate leaders can focus on improving digital infrastructure and capabilities in order to empower their enterprises. They should also promote cross-industry collaboration and knowledge sharing in order to foster innovation. This allows them to potentially replicate the beneficial results found in the Chinese AV business.

6. Conclusions and Implications

Following the discussion of the research findings, this study arrives at its conclusions and further deduces implications, limitations, and future scope.

6.1. Conclusions

The study suggests that digital empowerment serves as the foundation for enhancing the innovation quality of Chinese AV companies. It then develops a theoretical model of "digital empowerment→digital platform capability→boundary-spanning search→innovation quality" that is based on the resource orchestration theory and the organizational search theory. The model examines the ways in which digital technology and digital infrastructure can improve the digital platform capability of core enterprises by empowering resources, structures, and ecosystems. This process encourages AV companies to continuously enhance their boundary-spanning search capability, thereby paving the way for the enhancement of their innovation quality.

The study subsequently conducts empirical substantiation through multiple hierarchical regression analysis and multiple econometric tests, based on 697 questionnaires from AV companies. The findings indicate that digital empowerment is a critical factor in the enhancement of innovation quality in AV companies. Digital platform capability and boundary-spanning search, respectively, play a partial mediating role between digital empowerment and innovation quality, while digital platform capability and

boundary-spanning search play a chain-mediating role between digital empowerment and innovation quality.

6.2. Implications

The research offers managers of AV companies in China valuable insights. Initially, it is imperative for AV companies to prioritize digital empowerment. In the context of resource empowerment, managers should prioritize the multifaceted accumulation, in-depth analysis, and rational application of data, as it is the fundamental component of digital empowerment. In order to more effectively optimize its product design in accordance with consumer needs, improve the performance and safety of AVs, and enhance innovation quality, the company should increase investment in key technologies such as artificial intelligence, sensors, and machine learning, and further enhance data management systems. In order to promote structural empowerment, managers should foster cross-departmental communication and cooperation, establish adaptable organizational structures, and ensure the efficient circulation of high-quality information and the sharing of knowledge within the organization. They should enhance the efficacy of innovation and response speed by reengineering their processes, and they should optimize their R&D and production processes in accordance with feedback from various departments. Managers should foster the high-quality development of innovation across the AV industry by actively participating in the ecosystem, which comprises 5G, charging infrastructure, intelligent transportation, and the Internet of Vehicles, and by establishing close cooperative relationships with suppliers, research institutions, and customers in terms of ecological empowerment.

Secondly, digital empowerment improves the quality of innovation by enhancing the digital platform capabilities of AV companies. Thus, it is imperative that AV companies prioritize their digital platform capabilities. Managers should establish an open ecosystem with external partners to facilitate the sharing of data and resources, as the digital platform serves as a conduit for communication with the external market, users, and partners in addition to serving as a tool for internal management and operations. In order to improve the integration capabilities of data throughout the supply chain, they should allocate significant resources to artificial intelligence and big data technologies. Moreover, the platform's data-processing capabilities, user interaction experience, and market response speed should be enhanced by optimizing functions and upgrading technology. Simultaneously, it is imperative for AV companies to attract and develop digitally proficient personnel to facilitate the efficient operation of the digital platform. This includes software engineers, data analysts, and user experience designers. They have the ability to enhance the quality of innovation by leveraging digital tools and platforms, thereby fostering the innovative growth of AV companies.

Thirdly, the research indicates the substantial contribution of the boundary-spanning search to the advancement and innovation of AVs. On the one hand, managers should actively pursue partnerships with other industries and fields, establish cross-industry collaboration platforms, and facilitate the exchange and cooperation between experts in various domains, including the automotive, internet, AI, vehicle networking, and high-precision mapping domains. This allows them to acquire new technologies and knowledge. Additionally, AV companies can accelerate the pace of innovation and collaboratively resolve technical challenges by attracting external innovators to participate in the company's R&D process through open innovation platforms. Conversely, it is imperative to facilitate the establishment and advancement of interdisciplinary teams. The promotion of communication and cooperation among employees from diverse backgrounds can be achieved by assembling teams with diverse backgrounds and professional knowledge, encouraging employees to develop cross-disciplinary thinking, and enhancing their understanding

and application abilities of different fields through training and education. Furthermore, promoting employees to collect information from a variety of sources, including academic research, industry reports, competitor analysis, and user feedback, can result in a more comprehensive understanding of technology and market trends. This method has the potential to generate novel solutions and perspectives during the innovation process.

Finally, the sustainable development of AV enterprises is reliant upon the establishment of a high-quality innovation system. For instance, Apollo Go, a prominent autonomous driving technology company, has invested more than five hundred billion yuan and continues to be at the forefront of the innovation and development of China's AV industry, with over 50,000 autonomous driving patents. Autonomous driving is a representative industry of the new productive force, as it is a novel business form. Currently, the road-testing network and commercial territory are expanding, with over 40 cities in the country having implemented regulations on the commercial application of AVs and road testing. Autonomous driving has expanded to encompass a wide range of application scenarios, including mining and logistics, in addition to daily travel. There is still a significant amount of potential for innovation in the future. Therefore, it is imperative to establish an innovative system of exceptional quality. The research and development of autonomous transportation technology are both challenging and expensive. Some digital technologies and components are presently subject to others, whether it is breaking through technical bottlenecks or cultivating new momentum for future industries. In order to increase the quality of innovation in areas such as algorithm development, sensor manufacturing, and system integration, we must have the key core technologies in our possession, leverage market demand and expectations as innovation traction, and manage the relationship between underlying technology research and development and commercial promotion. The two complement each other, maximize the utility of digital platform capabilities and the boundary-spanning search, concentrate and integrate multiple forces to conduct innovative activities in collaboration, and foster positive interaction and joint research and development among various parties, including policies and regulations, research and production, and market promotion. A global lead in autonomous driving innovation technology can be achieved by addressing the current phenomenon of "quantitative progress, quality limping" in China's autonomous driving innovation and development. Accelerating the large-scale application of innovation results and digital technology innovation will facilitate the advancement of autonomous transportation, establishing a collaborative effort.

6.3. Research Limitations and Future Scope

This study has certain limitations, and future research and discussion can be conducted in greater depth based on this information. One initial step is to gather sample data from various regions of the country. However, the development level of AVs varies considerably among different regions in China due to the fact that this is an emerging industry. Significant phase differences exist among the eastern, central, and western regions with respect to policy and regulations, development road testing, and commercial operations. The samples in this study, however, are primarily from certain developed areas and do not adhere to the regional division based on the development level of AVs, as a result of the principles of sample selection and data availability. Thus, the samples can be supplemented in the future to yield more global-scale regional conclusions. Second, this study has a certain guiding significance for the AV industry; however, the applicability of the research conclusions to other industries must still be confirmed. In turn, the impact mechanism and impact path of digital empowerment on the quality of corporate innovation in other sectors can be further investigated and analyzed in the future. Third, the study did not incorporate relevant moderating variables into the model as a result of the research model's complexity,

as well as time and resource constraints. In the future, additional variables that may moderate the mechanism of action on the innovation quality of AV enterprises, such as knowledge coupling and flexible convention, could be incorporated to enrich and extend the theoretical model of this study. Fourth, the questionnaire survey method is employed in this study to gather static cross-sectional data from managers. However, the process of innovation and development for AV companies necessitates dynamic monitoring. Cross-sectional data research is unable to provide a comprehensive description of the relationship between variables. Therefore, longitudinal tracking can be employed to undertake a dynamic demonstration and analysis of the impact of digital empowerment on the innovation quality of AV companies in the future. Finally, this study employs quantitative methods to substantiate its arguments. Future research may use qualitative methodologies, such as case studies, to blend quantitative and qualitative findings, resulting in more persuasive conclusions.

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