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Does the development of cross-border e-commerce improve the digital transformation of export enterprises?—Evidence from the comprehensive pilot zones for cross-border e-commerce

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Abstract. Based on data on Chinese A-share listed export enterprises from 2013 to 2023, this paper examines the impact and mechanisms of the comprehensive pilot zone policy for cross-border e-commerce on the digital transformation of export enterprises against the background of the integration of the digital economy and the real economy. The empirical results show that the establishment of the pilot zones significantly promotes enterprise digital transformation, mainly through two paths: increasing government digital subsidies and improving the business environment, thereby intensifying market competition. It is further found that policy radiation intensity has a significant digital transformation effect on export enterprises, in which the three types of instruments—government digital support, market competition and business environment, and digital platforms and public service supply—all play a role to varying degrees. Accordingly, differentiated and targeted support should be provided, digital infrastructure should be improved by relying on the pilot zones, and the flow of digital factors should be facilitated.

Keywords: enterprise digital transformation, cross-border e-commerce, digital subsidies, market competitiveness, digital technology

1. Introduction

In recent years, with the deep integration of digital technology and international trade, cross-border e-commerce has become an important way to promote the development of new forms of foreign trade and to enhance enterprises' participation in international market competition. As an important vehicle for advancing the development of cross-border e-commerce and institutional innovation, China has successively established comprehensive pilot zones for cross-border e-commerce since 2015, aiming to provide institutional support for enterprises' cross-border business through policy arrangements such as customs clearance facilitation, tax support, financial services, logistics coordination, digital platform construction and public service supply. The comprehensive pilot zone is an institutional innovation arrangement that has been continuously expanded and improved across cities and stages; therefore, whether the policy can promote enterprise digital transformation

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and through which paths this effect is realized still leaves room for further discussion. In this context, a comprehensive clarification of how the comprehensive pilot zones affect enterprise digital transformation through institutional innovation and differences in policy intensity is of practical significance for evaluating the implementation effects of pilot zone policies and optimizing the supply of policy content.

Two strands of literature are closely related to this study. One strand discusses the connotation and benefits of cross-border e-commerce in China. At present, scholars have not reached a unified conceptual definition of cross-border e-commerce, but most studies hold that its main feature lies in the fact that transactions are conducted through e-commerce platforms. Scholars at home and abroad explain the connotation of cross-border e-commerce from different perspectives; specifically, cross-border e-commerce refers to a new form of trade in which transaction entities in different customs territories conduct commodity transactions, payment settlement, cross-border logistics transportation and transaction completion with the help of e-commerce platforms [1]. From the perspective of technological attributes, cross-border e-commerce reflects the in-depth application of digital technology in international trade. Cross-border e-commerce is an in-depth application of digital technology, and the two trading parties therefore break through the constraints of time and space, carrying out inquiry and price negotiation, communication and consultation, and contract conclusion in the transaction process [2, 3].

As regards the role and characteristics of cross-border e-commerce, over the past decade or so, relying on the cross-border e-commerce policies introduced by the state, it has not only strongly promoted the growth of China's foreign trade, significantly increasing cross-border e-commerce exports in various industries within cities [4], but has also become an important engine driving the economy. Even in the face of the impact of the COVID-19 pandemic and turbulence in the external situation, the growth rate of the cross-border e-commerce market remained substantially ahead of the growth pace of China's foreign trade exports [5], and in 2024 cross-border e-commerce imports and exports grew by 10.8%, with their share of foreign trade rising to 6% [6]. The reason is that cross-border e-commerce is driven by digital factors and, by exploiting the characteristics of spatial boundlessness and digitized transaction media, has built a globally unified cross-border e-commerce market platform that enables international participants to conduct cross-border transactions more stably and conveniently [7].

The other strand of literature discusses the measurement and driving factors of enterprise digital transformation. With the increasing availability of enterprise textual data, the keyword frequency statistics method based on text mining has gradually become an important approach to measuring enterprise digital transformation. This method mainly extracts and counts digitalization-related characteristic words from textual materials such as enterprise annual reports and patent application documents, so as to reflect the level of enterprises' digital technology application and digital transformation. Existing studies have pointed out that, by conducting textual analysis of listed companies' patent application documents, screening digitalization-related keywords and counting the number of applications, the value plus one is taken as a natural logarithm to construct a measurement indicator [8]; some scholars, based on the annual report texts of Chinese listed companies, count the frequencies of digitalization characteristic words such as "artificial intelligence", "big data" and "cloud computing", and construct a relatively robust digital transformation index through base-period processing [9-11]. At the same time, some studies point out that simple word frequency statistics under an equal-weight setting may overestimate the role of general-purpose digital technologies and ignore differences in enterprises' dependence on different digital technologies; therefore, methods such as Term Frequency–Inverse Document Frequency (TF-IDF) have been further introduced to improve the accuracy of digital transformation measurement at the micro level [12]. On this basis, some scholars advocate constructing a multidimensional comprehensive evaluation system by integrating multi-source data, evaluating enterprise

digital transformation from dimensions such as digital awareness, digital capability, digital performance, strategic guidance, infrastructure construction, service support and factor input, and determining indicator weights by principal component analysis, the entropy method, the analytic hierarchy process and expert scoring [8]. Overall, existing research has gradually expanded from single text-based word frequency measurement to multidimensional comprehensive indicator evaluation, which serves as the methodological basis for quantitative research on the level of enterprise digital transformation.

As for the drivers of enterprise digital transformation, from an interdisciplinary perspective, enterprise digital transformation involves not only technological change but also an all-round reshaping of organizational structure, strategic layout and cultural concepts [13]. Following the establishment of these quantitative methods, most existing studies further explore the direct effects of digital transformation on firms. Some studies argue that digital transformation helps promote entrepreneurial activities and stimulate entrepreneurial vitality in manufacturing enterprises [14], enhances firms' risk resistance [15], and significantly raises the level of specialized division of labor among Chinese listed firms, analyzing the micro-level effects of digital transformation on firms from these perspectives [10]. However, emphasizing only the micro-level changes that digital transformation brings to firms is not comprehensive; the analysis needs to be extended to the macro level. Digital transformation not only brings substantive innovation to firms but also innovation in their overall strategic layout [16], while firms also pay more attention to building core competitiveness, especially cultivating digital competitiveness [17]; some scholars further analyze how digital transformation promotes breakthrough innovation in firms' management and operating models from multiple firm-level dimensions such as organizational structure, marketing and production, product design and R&D [18].

The possible marginal contributions of this paper include the following. First, in terms of measuring enterprise digital transformation, it constructs a comprehensive measurement method of "annual report text analysis + structured variables + XGBoost". It breaks through the possible measurement bias of the existing keyword frequency method, which may "emphasize disclosure while neglecting practice", introduces structured variables such as the number of digital technology patent applications, the number of software copyrights, R&D investment and R&D personnel, and uses the XGBoost method to fuse text features with information on firms' actual digital input and output, thereby portraying the level of enterprise digital transformation more comprehensively and providing a reference measurement approach for quantitative research on enterprise digital transformation. Second, in terms of policy quantification, it constructs a policy radiation intensity indicator. Traditional DID variables mainly identify whether the city where a firm is located has established a comprehensive pilot zone for cross-border e-commerce, and can hardly capture the degree to which a firm is actually affected by the policy. Based on policy texts, this paper constructs a policy radiation intensity indicator at the city–year level for export enterprises and forms a firm-level policy radiation intensity variable; on this basis, it identifies the differentiated effects of different policy contents on enterprise digital transformation, providing an analytical framework with greater explanatory power for evaluating the micro-level effects of regional pilot policies.

2. Research background and theoretical mechanism hypotheses

The comprehensive pilot zone policy for cross-border e-commerce helps advance the process of enterprise digital transformation. From the perspective of policy supply, the policy can reduce enterprises' operating costs, search costs, communication costs and logistics costs, helping them overcome difficulties of varying degrees such as insufficient transformation capacity, excessively high transformation costs and excessively long transformation periods [19], thereby injecting impetus into enterprise digital transformation. A notable

feature of the policy is that it is data-driven and supported by digital technology. Specifically, by establishing information-sharing mechanisms, it improves the information asymmetry between enterprises and financial institutions, enabling enterprises to enjoy preferential policies more equitably and thus stimulating enterprise digital transformation [20]. In addition, the comprehensive pilot zones attach importance to and strive to improve digital infrastructure; their core strategy is to leverage the global digital network advantages of digital platforms to provide one-stop services for enterprises and promote enterprise digital transformation [7]. For example, under policy guidance in Hangzhou, enterprises in the comprehensive pilot zone have settled on Alibaba International Station and used the platform's digital marketing tools to precisely target global customers, driving enterprise digital transformation.

From the perspective of enterprise effects, the digital demonstration effect brought by the comprehensive pilot zones can guide enterprises to optimize their resource allocation, and through resource allocation strategies that span cities and countries and integrate online and offline channels, effectively empower local enterprises' digital transformation [21]. At the same time, the pilot zones provide support to enterprises in the region in many respects, such as capital settlement, logistics transportation and digital marketing. This not only stimulates enterprises to strengthen their digital competitiveness but also enhances their digital innovation capacity by introducing and applying digital technology, laying the foundation for digital transformation. Next, this paper analyzes how digital economy policies incentivize enterprise digital transformation from two aspects: digital subsidies and market competitiveness.

Hypothesis 1: The comprehensive pilot zone policy for cross-border e-commerce can promote the digital transformation of export enterprises.

2.1. Digital subsidies

Industrial policy theory refers to the government intervening in and guiding industrial development through policy means in order to achieve economic growth, structural optimization and enhanced competitiveness. Local governments, based on their own resource endowments and competitive advantages, clarify the development goals of the pilot zones and, by formulating digital subsidy policies, help the comprehensive pilot zones develop rapidly. For example, Hangzhou was the first comprehensive pilot zone for cross-border e-commerce in China; to advance its construction, the government issued policies granting reasonable annual funding support to enterprises participating in cross-border e-commerce talent incubation projects and providing logistics and warehousing support subsidies to cross-border e-commerce enterprises that purchase capacity from logistics firms. These government subsidies can drive enterprise digital transformation, mainly in two respects: the hard environment and the soft environment. In terms of the hard environment, during policy implementation governments often increase financial support for local enterprises and optimize and upgrade digital infrastructure construction, so as to stimulate the impetus for enterprise digital transformation [22]. In terms of the soft environment, the government releases policy-based resource dividends to talent, stimulating the agglomeration of digital talent and forming a "geese formation effect", which promotes R&D effects and the convergence of talent [23], thereby enhancing enterprises' digital transformation capacity and level of digital technology R&D [19]. In addition, when the vigorous development of digital enterprises prompts enterprises to increase digital investment [24], many enterprises, facing financing constraints that leave them "afraid to transform", tend to allocate resources in priority to short-term projects that can quickly generate returns [25]; digital subsidies can directly increase enterprises' cash flow, enabling them to expand investment in digital transformation.

At the same time, institutional economics holds that market operation does not rely entirely on the price mechanism to achieve optimal resource allocation automatically, and that the institutional environment

likewise has an important impact on enterprise behavior and resource allocation efficiency. The environment created by the comprehensive pilot zones plays a fundamental supporting role in the process of enterprise digitalization [26], and under the coordinated advancement of digital policies it promotes the efficient allocation of enterprise resource factors and pushes the industrial structure towards the high end [27]. Based on the above analysis, the following hypothesis is proposed.

Hypothesis 2: The establishment of comprehensive pilot zones can enable export enterprises to obtain more policy-based resources represented by government fiscal resources, prompting enterprises to allocate more resources to digital transformation.

2.2. Market competitiveness

By lowering entry thresholds and improving digital infrastructure, the pilot zones attract a large number of enterprises to enter, leading to a decline in market concentration and a marked intensification of homogeneous competition. Within the framework of market competition theory, market competitiveness is an important basis for enterprises' technology choices and transformation paths; because the market follows the development rule of "survival of the fittest" and exhibits "peer effects", enterprises facing competitive pressure will proactively maintain their competitive advantage in the cross-border e-commerce industry through digital transformation [28]. Through digital technology, enterprises can substantially reduce costs such as information search, transaction negotiation and execution supervision, and restructure transaction processes to improve efficiency. This transformation not only optimizes enterprises' overall operations but also compels them to enhance their innovation capacity: in order to stand out in fierce competition and meet diversified market demands, enterprises must accelerate technological iteration and explore new products, new models and new ecosystems, thereby significantly strengthening their overall innovative vitality and capability. On the one hand, the pilot zones help attract more enterprises to enter the pilot areas and stimulate competition among cross-border e-commerce enterprises; on the other hand, they help enterprises explore overseas markets. The pilot zones have established convenient services such as "online service platforms" and a "single window", simplifying business processes and lowering entry thresholds; as the number of enterprises continues to grow, market concentration declines and market competition intensifies [29]. Against the background of a new round of information technology transformation, and further considering the facilitation of enterprise business in the pilot zones, the active implementation of customs clearance facilitation policies and measures and the improvement of overseas warehouse networks and smart logistics platforms can broaden the trade cooperation channels of cross-border e-commerce enterprises in the pilot zones and form a large-scale market; the expansion of market opportunities may trigger fierce market competition [17].

Transaction cost theory holds that enterprises, in order to improve competitiveness, are more inclined to reduce search costs and information costs; what enterprises pursue is "cost reduction and efficiency improvement", namely low cost and high efficiency. In terms of cost, cross-border e-commerce enterprises face cost problems such as labor and logistics in the transaction process, and at this point enterprises tend to choose, between the market and the pilot zone, whichever has lower transaction costs; for example, digital technology can substantially reduce the costs of information acquisition, negotiation, supervision and execution, restructuring the transaction mechanism to improve efficiency and cope with complexity. Therefore, low costs enable enterprises to gain competitive advantage and further promote their digital transformation. In terms of efficiency, the new factor theory holds that production factors are not limited to labor, land, capital and entrepreneurship, and that technology and information play an increasingly important role; digital technological change stimulates consumers' large demand for related products, and enterprises satisfy diversified and varied demands as far as possible through competition so as to form a considerable

market scale and realize the "long tail effect", accelerating their own digital transformation by continuously meeting customers' efficiency requirements [30]. In addition, the digital era has changed the pattern of market competition, and the retail industry is more inclined to shift sales towards young, dynamic digital enterprises [13]. It is worth noting that in the newly released 2024 ranking of Chinese listed companies by market value, Tencent Holdings ranks first; as an internet enterprise, it has continuously improved its digital competitiveness, gained new competitive advantages and thus realized enterprise digital transformation. Based on the above analysis, the following hypothesis is proposed.

Hypothesis 3: The establishment of comprehensive pilot zones increases the intensity of market competition, thereby promoting the digital transformation of export enterprises,as shown in Figure 1.

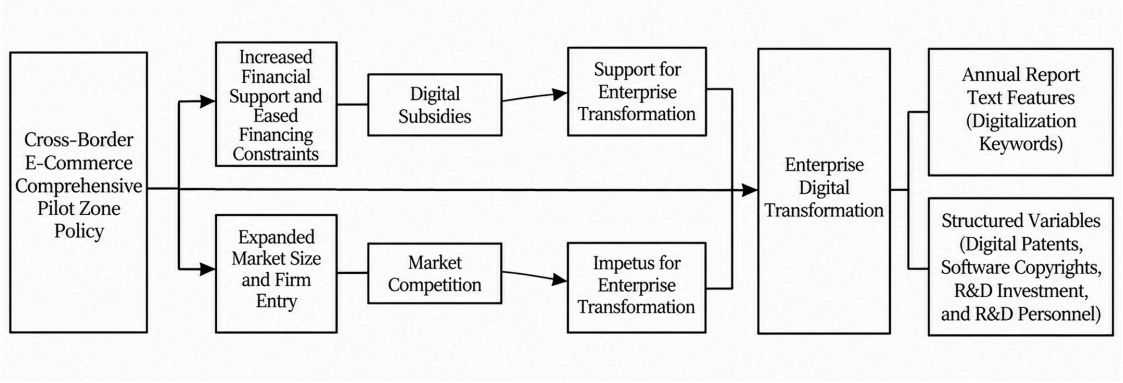


Figure 1. Mechanism diagram of the impact of the comprehensive pilot zone policy for cross-border e-commerce on enterprise digital transformation

3. Research design and stylized facts analysis

3.1. Data processing

The micro-level enterprise data come from the annual reports disclosed by A-share listed companies, covering indicators such as firm size, asset-liability ratio, firm age, return on total assets, operating revenue growth rate and capital intensity for 2013–2023. The selected samples are cleaned and processed as follows: (1) samples of financial enterprises, ST enterprises and enterprises delisted during the research period are excluded; (2) samples that do not meet the requirements of generally accepted accounting principles and have missing data on key variables are excluded; (3) to avoid extreme values interfering with the regression results, all continuous variables are winsorized at the 1st and 99th percentiles.

3.2. Indicator design for the digitalization level of export enterprises

To measure the level of enterprise digital transformation more comprehensively, building on the traditional annual report text word frequency method and drawing on the idea of hybrid models in ensemble learning, this paper constructs a new measurement indicator of enterprise digital transformation based on "text analysis + XGBoost", namely $DIGITAL_LEVEL_{ict}$, which is divided into the following three steps:

3.2.1. Building training labels

This article first creates a digital keywords dictionary based on annual reports of listed companies and counts the frequency of digital keywords in each report. Considering the variation in the length of annual reports across different companies, this study constructs a company's digital text score using the proportion of digital

keyword occurrences to the total number of words in the report, and then apply a logarithmic transformation (Equation (1)):

$$TextScores_{it} = ln\ (1 + \frac{Digitalwords_{it}}{Totalwords_{it}} \times 1000) \quad (1)$$

Here, $Digitalwords_{it}$ represents the total number of times digital keywords appear in company's annual report in year t, and $Totalwords_{it}$ represents the total number of words in that annual report. This paper uses this text score as the training label for the XGBoost model.

3.2.2. Introduction of structured variables

To avoid the measurement bias that may arise from a single source of text disclosure, structured variables such as enterprise digital technology patents, software copyrights, the number of apps and R&D investment are further introduced to characterize enterprises' actual performance in digital technology innovation, digital asset accumulation and digital business layout.

3.2.3. Building indicators for enterprise digitalization levels

This paper uses the XGBoost model to merge text features with structured features, perform binary classification probability prediction , and generate a comprehensive digital transformation score for enterprises called $DIGITAL_LEVEL_{ict}$ (Equation (2)). The scale of the keyword dictionary, the set of structured variables, hyperparameters, cross-validation schemes, and scores are all standardized across all firm-year observations to preserve the changes in firms' digital transformation levels over time.

$$\widehat{DIGITAL_LEVEL}_{ict} = \sigma(\sum_{t=1}^{T} \eta f_t(x)) \quad (2)$$

x is the input feature vector, including basic probabilities from text analysis and other numerical features. $f_t(x)$ represents the decision tree generated in the t-th iteration. η is the learning rate, controlling each tree's contribution to the final model. T is the number of iterations (the number of decision trees). σ is the Sigmoid function, used to convert output values into probabilities between 0 and 1. The higher this value, the higher the company's level of digital transformation.

Compared with traditional word frequency indicators, this article's metrics add structured variables like digital technology patents, software copyrights, and R&D investment, showing that beyond the usual text disclosure, they further reflect a company's actual digital technology innovation and digital resource investment.

3.3. Construction of the firm-level policy radiation intensity indicator

This paper systematically collects policy texts related to the comprehensive pilot zones for cross-border e-commerce through Python web crawlers. The main data sources are the websites of the State Council, the Ministry of Commerce, the General Administration of Customs, the State Taxation Administration, the State Administration of Foreign Exchange, and the municipal people's governments and commerce authorities of the pilot zone cities; the search keywords include "comprehensive pilot zone for cross-border e-commerce", "cross-border e-commerce comprehensive pilot zone", "implementation plan", "several measures", "support policies", "special funds" and "overseas warehouse". To ensure the relevance and authority of the policy texts, this paper excludes news reports, meeting notices, investment promotion materials and texts without substantive policy provisions, retaining only policy documents that can be clearly matched at the city–year level.

3.3.1. Topic identification and semantic modeling

Table 1. Keyword spectrum of policy intensity sub-items of the comprehensive pilot zones for cross-border e-commerce

Category	Keywords
Government digital support	fiscal subsidies, fiscal support, special funds, support funds, awards, grants, award-and-subsidy schemes, funding support, fund support, policy support, policy backing, tax incentives, tax relief, tax and fee reductions, export tax rebates, rebate facilitation, tax exemption without invoices, deemed collection, financing support, financial support, credit support, loan interest subsidies, financing facilitation, financing services, guarantee support, insurance support, credit insurance, export credit insurance, funds, industrial funds, guidance funds, policy-based financing, inclusive finance, supply chain finance, cross-border finance
Market competition and business environment	market entities, entity cultivation, enterprise cultivation, business incubation, entrepreneurial innovation, innovation and entrepreneurship, brand cultivation, demonstration enterprises, leading enterprises, small and medium-sized enterprises, trade facilitation, customs clearance facilitation, customs clearance efficiency, customs clearance, customs declaration, inspection, inspection and quarantine, regulatory innovation, regulatory models, customs supervision, checklist-based release, consolidated declaration, simplified declaration, facilitated customs clearance, export supervision, return supervision, cross-border settlement, payment settlement, foreign exchange facilitation, logistics facilitation, cross-border logistics, international logistics, warehousing, overseas warehouses, public overseas warehouses, bonded warehouses, supply chains, supply chain services, public services, public service systems, business environment, facilitation, filing, approval, process optimization, one-stop services, comprehensive services, service systems, online declaration
Digital demand expansion and public service supply	digital platforms, online platforms, public service platforms, comprehensive service platforms, cross-border e-commerce platforms, e-commerce platforms, information platforms, service platforms, data platforms, digital trade platforms, data sharing, information sharing, information services, digital services, digitalization services, technical services, technical support, digital marketing, online marketing, precision marketing, online transactions, online trading, intelligent supervision, smart supervision, intelligent services, informatization, digitalization, big data, cloud computing, blockchain, artificial intelligence, e-ports, single window, international trade single window, digital trade, cross-border e-commerce big data, data analysis,
Digital demand expansion and public service supply	data management, digital talent, talent training, talent introduction, talent services, training bases, incubation platforms, innovation platforms

Referring to the classification of policy instruments in existing findings by Rothwell and Zegveld in 1985, policy instruments can usually be divided into three types: supply-oriented, environment-oriented and demand-oriented. Supply-oriented instruments mainly reflect the government's direct support for enterprise development through the supply of factors such as capital, technology, talent, information and infrastructure; environment-oriented instruments mainly reflect the government's reduction of enterprise operating costs and optimization of external development conditions through institutional norms, regulatory optimization, tax and finance, customs clearance facilitation and business environment improvement; demand-oriented instruments

mainly expand enterprises' market demand and development space through government procurement, market expansion, demonstration applications and international cooperation. On this basis, and in light of the specific content of the pilot zone policy texts, this paper divides policy content into three categories—government digital support, market competition and business environment, and digital platforms and public service supply—and constructs a keyword dictionary for each policy intensity sub-item, with the specific classification shown in the Table 1 below.

3.3.2. Weight construction

In the specific measurement, this paper counts the frequencies of the three categories of policy intensity sub-item keywords in the policy texts of city c in year t, and standardizes the three word frequency indicators to obtain the policy intensity of government digital support, $SubsidyPolicy_{ct}$, the policy intensity of market competition and business environment, $MarketPolicy_{ct}$, and the policy intensity of digital technology flow, $TechPolicy_{ct}$. Furthermore, this paper constructs a comprehensive policy radiation intensity indicator (Equation (3)):

$$PRI_{ct} = \frac{1}{3}\left(SubsidyPolicy_{ct} + MarketPolicy_{ct} + TechPolicy_{ct}\right) \tag{3}$$

This article uses an equal-weight method to create a comprehensive policy radiation intensity index, aiming to reduce the impact of subjective weighting on the construction of the indicator. PRI_{ct} denotes the policy radiation intensity of the comprehensive pilot zones for cross-border e-commerce of city c in year t. The larger the value of this indicator, the richer the supply of policy instruments in that city in that year, and the higher the policy radiation intensity reflected in the policy texts.

Based on the policy instrument information in the policy texts, the policy radiation intensity indicator PRI of the comprehensive pilot zones characterizes the intensity of policy supply in different cities and periods from dimensions such as digital infrastructure, customs clearance facilitation, fiscal and tax support, financial services, logistics and warehousing, platform services, and talent and technical support, and further measures the actual radiation of the policy on micro-level enterprises in combination with enterprises' industry attributes, export attributes and digitalization foundations.

Thus, the firm-level policy radiation intensity is obtained, which is used to characterize the intensity of policy radiation that a firm actually receives from the comprehensive pilot zones (Equation (4)):

$$FirmPRI_{ct} = treat_c \times post_{ct} \times PRI_{ct} \quad (4) \tag{4}$$

3.4. Stylized facts on the comprehensive pilot zones and the digitalization level of export enterprises

Based on the evolution of pilot zone policies, Figure 2 shows the annual trends in the level of enterprise digital transformation and the total number of policies related to the comprehensive pilot zones from 2013 to 2023. The total number of related policies refers to the number of policies collected and compiled nationwide from public channels such as the State Council, the Ministry of Commerce, the General Administration of Customs and local governments, accumulated year by year according to the release date. It can be seen that the cumulative number of policies for the comprehensive pilot zones has grown continuously since 2015, and the level of enterprise digitalization also rose overall during the sample period, gradually shifting from negative to positive territory after 2018; the two show a relatively consistent upward trend after 2015.

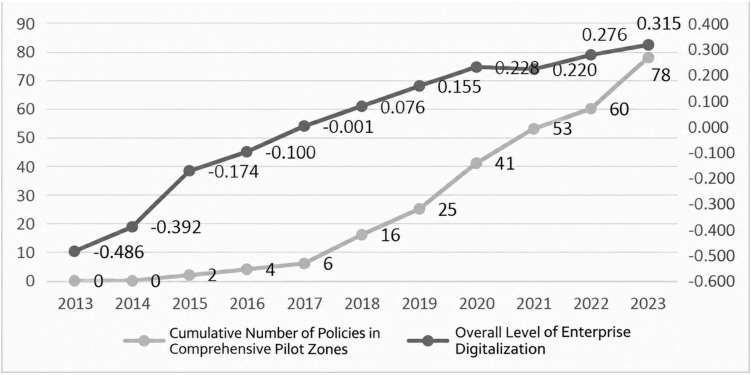


Figure 2. stylized facts on the cumulative number of policies and the level of enterprise digitalization, 2013–2023

Overall, as an important institutional arrangement for advancing digital trade and new forms of foreign trade, the comprehensive pilot zones show a certain co-movement between the continuous increase in policy supply and the improvement in enterprise digitalization, suggesting that pilot zone policies may provide external institutional conditions for enterprise digital transformation by optimizing the cross-border transaction environment, improving public service platforms, strengthening policy support and expanding digital trade scenarios.

4. Empirical analysis

4.1. Empirical model specification

First, this paper uses the Difference-in-Differences (DID) method to examine the impact of the establishment of comprehensive pilot zones on enterprise digital transformation; the basic model is specified as follows (Equation (5)):

$$DIGITAL_LEVEL_{ict} = \alpha + \beta treat_c \times post_{ct} + \delta X_{ict} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (5)$$

where $DIGITAL_LEVEL_{it}$ is the dependent variable; the subscripts i, c and t denote firm, city and year respectively, and it represents the digital transformation level of firm i in city c in year t; $treat_c$ is a dummy variable for whether the city belongs to a comprehensive pilot zone for cross-border e-commerce, taking the value of 1 if it is located in a pilot zone and 0 otherwise; $post_{ct}$ indicates whether the city is in the period after the implementation of the pilot zone policy in year t. If the city in which city c is located had already been approved as a comprehensive pilot zone in year t or earlier, $post_{ct}$ takes the value of 1 and 0 otherwise. X_{ict} denotes the time-varying control variables that may affect the level of enterprise digitalization; this paper controls for firm size, asset-liability ratio, firm age, return on total assets, operating revenue growth rate, capital intensity, whether the chairman and the general manager are the same person, the shareholding ratio of the largest shareholder, Tobin's Q and operating revenue. μ_i is the firm fixed effect; λ_t is the year fixed effect; ε_{ict} is the random disturbance term [9, 31]

Second, because the traditional DID model may suffer from control variable selection bias and deficiencies in its underlying assumptions when evaluating policy effects, this paper applies Double/Debiased Machine Learning (DDML) to the robustness tests in the empirical section, so as to further investigate the impact of the establishment of comprehensive pilot zones on enterprise digital transformation.

Double machine learning can effectively characterize nonlinear relationships among variables and [32], based on the idea of orthogonalization, removes the influence of high-dimensional confounding variables on the "quasi-natural experiment", so that an unbiased estimate of the policy treatment effect can be obtained under finite samples. Accordingly, a partially linear model of double machine learning is constructed as follows (Equation (6)):

$$DIGITAL_{ct+1} = \theta_0 DID_{ct} + g(X_{ict}) + U_{ct}$$
$$E\ (U_{ct}(DID_{ct}|X_{ict}) = 0 \tag{6}$$

If machine learning is used to directly solve for $g(X_{ict})$ in the above model, the resulting estimated coefficient $\hat{\theta}$ is a regularized estimator that is biased in finite samples; therefore, an auxiliary regression is further constructed (Equation (7)):

$$DID_{ct} = m(X_{ict}) + V_{ct}$$
$$E(V_{ct}|X_{ict}) = 0 \tag{7}$$

where the functional form $m(X_{ict})$ is unknown and V_{it} is the error term with a conditional mean of 0. Therefore, this paper uses machine learning algorithms to estimate $\widehat{m}(X_{ict})$, and constructs the residual estimate $\widehat{V}_{ct} = Event_{ct} - \widehat{m}(X_{ict})$.

To improve the robustness of model estimation, this paper adopts multiple methods to process the regression samples in the subsequent regressions to obtain the final estimation results [28].

4.2. Baseline estimation results

Table 2 presents the baseline regression results.

Table 2. Baseline regression results

	(1)	(2)	(3)	(4)
did	0.4848***	0.0655***	0.4727***	0.0616***
	(0.059)	(0.020)	(0.078)	(0.021)
Control variables	No	No	Yes	Yes
Firm fixed effects	No	Yes	No	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Province × year fixed effects	Yes	Yes	Yes	Yes
Observations	23,435	23,435	23,435	23,435
Adjusted R^2	0.0813	0.8853	0.1455	0.8876

Note: Robust standard errors clustered at the city level are reported in parentheses; ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

4.3. Parallel trend test

Considering that the number of samples in years far from the policy implementation date is relatively limited, this paper merges the three years before implementation and earlier years and uses the year immediately preceding implementation as the base period for the parallel trend test. As can be seen from Figure 3, before policy implementation the estimated coefficients of the treatment group and the control group do not pass the significance test and their confidence intervals all include 0, indicating that there is no significant trend difference before implementation and that the parallel trend assumption holds. After implementation, the

estimated coefficients are positive overall and show a continuous upward trend, confirming that the pilot zone policy can continuously promote enterprise digital transformation.

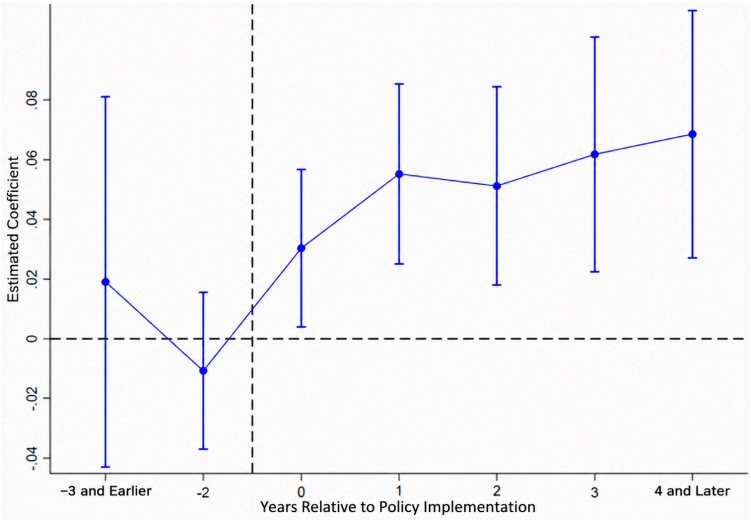


Figure 3. Parallel trend test

4.4. Robustness tests

4.4.1. Placebo test

This paper constructs new treatment and control groups by randomly drawing samples 500 times and conducts a placebo test to reduce the influence of unobservable factors; the results are shown in Figure 4. The estimated coefficients from 500 random permutations are mostly centered around 0, while the actual DID estimate is on the right tail of the permutation distribution. The two-sided empirical *p*-value is 0.002, indicating that it is unlikely that the baseline estimate is driven by random factors.

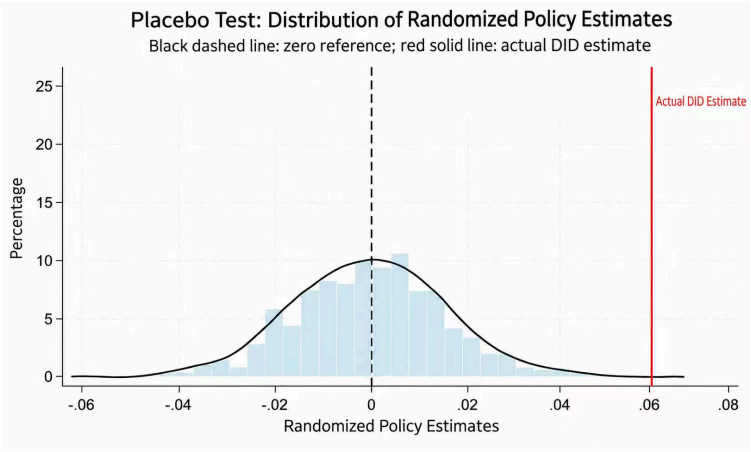


Figure 4. Placebo test

4.4.2. Adjustment of the sample scope

First, considering that outliers in the regression sample may bias the estimation results, and to ensure the robustness of the regression analysis, this paper conducts the regression analysis after winsorizing at the 5th and 95th percentiles in the baseline regression. As shown in column (1) of Table 3, the regression result after winsorizing is significantly positive, indicating that the baseline regression results of this paper are robust.

Second, given that the four municipalities directly under the central government—Beijing, Shanghai, Tianjin and Chongqing—enjoy special and significant advantages in creating a policy environment and advancing infrastructure construction, including them in the city sample may bias the research results. On this basis, this paper excludes Beijing, Shanghai, Tianjin and Chongqing from the sample cities and re-runs the regression on the remaining sample. As shown in column (2) of Table 3, the regression result after adjusting the sample is significantly positive, indicating that the baseline regression results are robust.

4.4.3. Changing the sample parameters

This paper further adjusts the model parameters to improve data utilization efficiency: the number of sample splits is set to 8, the number of repeated samplings is set to 101, and the results are re-estimated. The estimation results in columns (3) and (4) of Table 3 show that, at the 1% significance level, the estimated coefficient of the pilot zone policy is positive and significant regardless of whether the sample split ratio or the number of repeated samplings is adjusted. This not only shows that the policy significantly promotes enterprise digital transformation but also demonstrates the robustness and reliability of the baseline regression results.

4.4.4. Further ruling out interference from other policies

In addition to considering the influence of the sample scope and sample parameters, attention should also be paid to interference from other non-negligible potential policy factors during the sample period that may affect enterprise digital transformation. Within the sample period of 2013–2023, it is conjectured that the pilot free trade zone policy implemented from 2015 and the comprehensive big data pilot zone policy issued in 2016 may bias the results of this paper. To enhance the robustness of model estimation, dummy variables for the implementation of the pilot free trade zone (fp) and the comprehensive big data pilot zone (bp) are added to the baseline regression model as controls. As can be seen from columns (5) and (6) of Table 3, after adding the two policies respectively, the coefficient of did remains significantly positive, indicating that the pilot zone policy has a significant effect in promoting enterprise digital transformation and further supporting the robustness of the research conclusions.

Table 3. Robustness tests

	(1)	(2)	(3)	(4)	(5)	(6)
did	0.0521**	0.0616***	0.0610***	0.0596***	0.0702***	0.1343***
	(0.0203)	(0.0215)	(0.0215)	(0.0214)	(0.0197)	(0.0212)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
fp-policy	No	No	No	No	Yes	No
bp-policy	No	No	No	No	No	Yes
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	23,435	23,435	23,435	23,435	23,435	23,435
Adjusted R^2	0.8790	0.8876	0.8869	0.8767	0.7229	0.7231

Note: Robust standard errors clustered at the city level are reported in parentheses; ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

4.4.5. Robustness test based on double machine learning

To further test the robustness of the baseline regression results, the double machine learning method is further introduced on the basis of the traditional DID model. Through cross-fitting and orthogonalization, double

machine learning can to some extent alleviate control variable selection bias, misspecification of nonlinear functional forms and estimation bias caused by high-dimensional confounding factors, thereby improving the reliability of policy effect estimation. Specifically, this paper adopts a partially linear double machine learning model, taking the pilot zone policy variable as the core treatment variable and variables such as firm size, firm age, asset-liability ratio, profitability, operating revenue growth rate, capital intensity, duality of chairman and general manager, shareholding ratio of the largest shareholder, Tobin's Q and operating revenue as control variables, and further absorbs firm fixed effects and year fixed effects.

First, this paper changes the sample split ratio in the cross-fitting process to test whether the estimation results are sensitive to the way samples are divided. Specifically, the number of cross-fitting folds is set to Kfolds = 3 and Kfolds = 8, and random forest models are used to fit the outcome variable and the treatment variable respectively. The results show that the estimated coefficients of the policy variable are 0.318 and 0.307 respectively, both significantly positive, indicating that under different sample split ratios the pilot zone policy still promotes enterprise digital transformation.

Second, this paper further changes the machine learning algorithm to test whether the estimation results are affected by the choice of a particular algorithm. Specifically, three types of algorithms—LassoCV, gradient boosting trees and neural networks—are used for estimation. Among them, LassoCV can handle variable selection and multicollinearity through regularization; gradient boosting trees can better characterize nonlinear relationships among variables; and neural networks can capture more complex nonlinear structures. The results show that under the LassoCV, Gradboost and Nnet models the estimated coefficients of the policy variable are 0.618, 0.398 and 0.424 respectively, all significantly positive at the 1% level.

Third, combining the estimation results under different sample split ratios and different machine learning algorithms, it can be found that the coefficient of the policy variable remains significantly positive under the main model specifications, indicating that after accounting for nonlinear relationships, high-dimensional control variables and differences in sample division, the pilot zone policy still significantly promotes enterprise digital transformation. Therefore, the baseline regression conclusions of this paper are fairly robust.

To avoid possible interference from specification bias in the double machine learning model on subsequent conclusions, this paper verifies the robustness of the conclusions from multiple dimensions. The specific measures are as follows: first, the sample split ratio of the double machine learning model is adjusted, changing the original 1:5 ratio to 1:3, so as to examine the potential impact of the sample split ratio on the conclusions; second, the machine learning algorithm is changed, replacing the original random forest algorithm with lasso regression, gradient boosting trees and neural networks, to explore the impact of different prediction algorithms on the conclusions; third, in view of the possible subjective specification of the partially linear model built on double machine learning, this paper further uses double machine learning to construct a more general interactive model, so as to analyze the impact of model specification on the conclusions. Specifically, the specifications of the main regression and the auxiliary regression are adjusted as follows (Equation (8)):

$$\begin{aligned} Y_{ct+1} &= g(Event_{ct}\ ,\ X_{ict}) + U_{ct} \\ Event_{ct} &= m(X_{ict}) + V_{ct} \end{aligned} \tag{8}$$

The estimated coefficient of the treatment effect obtained from the interactive model is (Equation (9)):

$$\check{\theta}_1 = E[g(Event_{ct}=1, X_{ict}) - g(Event_{ct}=0, X_{ict})] \tag{9}$$

The regression results after adjusting the double machine learning model are reported in Table 4. The results show that when key elements such as the sample split ratio, the choice of machine learning algorithm, the model estimation approach and endogeneity treatment change, the core conclusion that the pilot zone

policy promotes enterprise digital transformation still holds. Although the quantified values of the policy effect fluctuate to some extent under different specifications, such variation only reflects adjustments in the magnitude of the effect and does not change the robustness of the conclusion.

Table 4. Robustness tests based on the double machine learning method

Variable	Kfolds = 3	Kfolds = 8	LassoCV	GradBoost	Nnet
did	0.062***	0.062***	0.062***	0.057***	0.066***
	(0.014)	(0.014)	(0.014)	(0.014)	(0.014)
Control variables	Yes	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	23,435	23,435	23,435	23,435	23,435

Note: Robust standard errors clustered at the city level are reported in parentheses; ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

5. Mechanism tests

Next, this paper examines the mechanisms through which the comprehensive pilot zone policy affects enterprise digital transformation from the two dimensions of digital subsidies and market competitiveness.

5.1. Increasing digital subsidies

As a key support instrument through which the government promotes enterprises' digital transformation and upgrading, digital subsidies play an important role in assisting enterprises' transformation and development; this paper first explores their impact on the digital subsidies enterprises obtain from the government.

Drawing on the annual reports of listed companies, this paper screens information on enterprises' receipt of digital subsidies according to keywords closely related to digitalization. Government digital subsidies are measured by whether an enterprise receives digital subsidies (subsidy_dummy) and the amount of digital subsidies (subsidy_amount) [13]. The results in columns (1) and (2) of Table 5 show that, after controlling for other influencing factors and fixed effects, the coefficients are all significantly positive, indicating that the pilot zones can effectively incentivize the government to introduce digital subsidy policies and bring enterprises more economic subsidies. This verifies the view of Hypothesis 2 of this paper.

5.2. Enhancing market competitiveness

As an important governance mechanism for enterprises, the market competition mechanism plays an important role in their transformation and development; this paper next explores its impact on market competitiveness. This paper uses the Herfindahl index to measure the degree of market concentration facing enterprises (hhl), which reflects the intensity of market competition. According to the results in column (3) of Table 5, the cross-border e-commerce pilot zone policies have noticeably lowered the Herfindahl index in the industries where companies operate, which means that industry market concentration has gone down and competition has gone up since the policies were put in place. This result aligns with the theoretical expectation that pilot zones boost competition by reducing market entry barriers and attracting companies, providing supporting real-world evidence for this competition channel.

Table 5. Mechanism tests

	(1)	(2)	(3)
	Whether digital subsidies are received	Amount of digital subsidies	hhl
did	0.1251***	1.7238***	-0.0123***
	(0.0092)	(0.1263)	(0.0032)
Observations	23,435	23,435	21,872
Adjusted R^2	0.0155	0.0164	0.0125

Note: Robust standard errors clustered at the city level are reported in parentheses; ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

6. Further discussion: the impact of policy radiation intensity and enterprise digital transformation

The comprehensive pilot zones constitute an institutional arrangement composed of multiple types of policy instruments, including fiscal support, tax incentives, customs clearance facilitation, logistics and warehousing, cross-border settlement, digital platform construction, technical services and talent training. Cities differ in the number of policy texts, the emphasis of policy content and the configuration of policy instruments, which may mean that the policy radiation intensity actually received by enterprises is not the same. Therefore, building on the DID identification framework above, this chapter further constructs a city–year level Policy Radiation Intensity indicator (PRI) for the comprehensive pilot zones, and examines the differentiated impact of the intensity of policy instrument supply on enterprise digital transformation.

6.1. Empirical model specification

To test the impact of policy radiation intensity on enterprise digital transformation, this paper specifies the following extended model (Equation (10)):

$$DIGITAL_LEVEL_{ict} = \alpha + \beta_1 \ (treat_i \times post_{it}) \ + \beta_2 FirmPRI_{ct} + \delta X_{ict} + \mu_i + \lambda_t + \varepsilon_{ict} \qquad (10)$$

To distinguish the level effects generated by the establishment of pilot zones from the marginal effects caused by policy radiation intensity, the extended model simultaneously controls for the baseline DID term and the policy radiation intensity variable at the enterprise level. β_1 is mainly identified by the differences in policy status before and after a pilot zone is approved, as well as between approved and unapproved cities, while β_2 is mainly identified by the cross-city and cross-year differences in policy intensity among approved cities during the policy implementation period. Here, PRI_{ct} represents the intensity of cross-border e-commerce pilot zone policy influence in city c in year t, and the rest of the variables and their meanings are consistent with the model set in Chapter 5.

In addition, to further identify the role of different policy instruments, this paper decomposes the comprehensive policy radiation intensity into three types of policy instruments and constructs the following sub-item indicators (Equation (11)):

$$DIGITAL_LEVEL_{ict} = \alpha + \beta \ (treat_i \times post_{it} \times PRI_{ct}) \ + \delta X_{ict} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (11) \qquad (11)$$

In addition, to further identify the sources of the role of different policy instruments, this paper decomposes the comprehensive policy radiation intensity into three categories—government digital support, market

competition and business environment, and digital platforms and public service supply—and constructs the following sub-item indicators respectively: $FirmSubsidy_{ict} = DID \times SubsidyPolicy_{ct}$; $FirmMarket_{ict} = DID \times MarketPolicy_{ct}$; $FirmTech_{ict} = DID \times TechPolicy_{ct}$, where $SubsidyPolicy_{ct}$, $MarketPolicy_{ct}$ and $TechPolicy_{ct}$ denote the intensity of the three types of policy instruments: government digital support, market competition, and digital platforms and public service supply, respectively. For the sample of enterprises exposed to export business, the following sub-item test model is further specified (Equation (12)):

$$DIGITAL_LEVEL_{ict} = \alpha + \beta_1 FirmSubsidy_{ict} + \beta_2 FirmMarket_{ict} + \beta_3 FirmTech_{ict} quad + \delta X_{ict} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (12)$$

6.2. Analysis of empirical results

Column (1) of Table 6 below shows that for export enterprises the coefficient of policy radiation intensity is significantly positive, indicating that the higher the policy intensity of the comprehensive pilot zones, the higher the level of digital transformation of export enterprises. Columns (2) to (4) further decompose the policy content; the results show that the three policy intensity sub-items—government digital support, market competition and business environment, and digital platforms and public service supply—differ in significance but are all significantly positive. It can be seen that cities with a richer supply of policy tools usually also have a higher level of enterprise digital transformation, but since PRI may be related to the city's potential digital capabilities, this result is understood as evidence related to expansion.

Table 6. Test of policy radiation intensity

	(1)	(2)	(3)	(4)
$FirmPRI_{ct}$	0.1833***			
	(0.0447)			
$FirmSubsidy_{ict}$		0.6018**		
		(0.2559)		
$FirmMarket_{ict}$			0.3734*	
			(0.2119)	
$FirmTech_{ict}$				0.6053***
				(0.2015)
Control variables	Yes	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations Adjusted R^2	22,304	22,304	22,304	22,304
Adjusted R^2	0.0662	0.7065	0.7064	0.7065

Note: Robust standard errors clustered at the city level are reported in parentheses; ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

7. Conclusion and prospect

In the digital era, digital transformation has become a core strategy for enhancing enterprise competitiveness and a key driver of global economic transformation and growth. Against this background, the Chinese

government has established comprehensive pilot zones for cross-border e-commerce to promote the formation and development of new trade models. As an important institutional innovation platform for advancing digital trade and promoting new forms of foreign trade, the comprehensive pilot zones provide a sound quasi-natural experiment setting for studying how the policy environment affects the digital transformation of export enterprises.

Based on data on export enterprises among Chinese A-share listed companies from 2013 to 2023, this paper investigates the impact of the establishment of comprehensive pilot zones on the digital transformation of export enterprises, and further conducts a systematic study through robustness tests, robustness tests based on double machine learning, mechanism tests and an extended analysis of policy radiation intensity. The findings are as follows: (1) the establishment of comprehensive pilot zones significantly promotes the digital transformation of export enterprises; (2) the mechanism results show that the comprehensive pilot zones effectively promote the digital transformation of export enterprises by increasing government digital subsidies, the digital subsidies received by companies have increased, and the market concentration in their industries has decreased, providing supporting evidence for the link between digital subsidies and market competition; (3) further analysis shows that the overall policy reach and its specific indicators are significantly positively related to the level of digital transformation in exporting companies, but this mainly reflects the link between the characteristics of the policy texts and the companies' digital levels, without implying a strict causal relationship.

First, popularize experience and amplify the demonstration effect of digital policy leadership. To strengthen the driving effect on the digital transformation of export enterprises, the mature experience and innovative models of the comprehensive pilot zones should be vigorously promoted. First, government digital subsidies should be used to improve the regional digital development environment and form digital industry clusters. Targeted subsidies should be provided according to the needs of export enterprises at different stages of digital transformation, so as to amplify the policy empowerment effect through the encouragement, support and guidance of digital industrial policy. Second, the platforms of the comprehensive pilot zones should be continuously optimized; through measures such as re-engineering customs clearance processes and improving tax rebate efficiency, public data resources in customs, taxation and logistics should be opened up in an orderly manner and shared at low cost, further enhancing policy coordination, greatly reducing the costs of export enterprises in cross-border e-commerce transactions and attracting more export enterprises to enter the pilot zones. Finally, the pilot areas of the comprehensive pilot zones should be gradually expanded, giving full play to their radiation, driving and demonstration effects on the digital economy, digital government and the digital development of export enterprises.

Second, implement differentiated policies and create a favourable market environment. For export enterprises, given the actual export conditions in different regions, the specific content of cross-border e-commerce policies should be refined and the digital transformation and upgrading of enterprises should be advanced step by step. Local market demand, regional economic development and industrial development advantages should be understood, and the applicable experience of existing comprehensive pilot zones should be applied and developed in light of local conditions, so that the advantages of regional location match the application scenarios. On the one hand, for export enterprises with weaker digital capabilities, support from fiscal and financial policies should be further increased, and support for the digital upgrading of export enterprises, the construction of digital systems, cross-border e-commerce talent training and the application of digital technology should be strengthened to lower the threshold for transformation. On the other hand, for export enterprises with stronger digital capabilities, market-oriented reform should be the focus. In addition, to prevent enterprises from exiting the market owing to unhealthy market competition, a fair and open market

competition environment should be actively created for export enterprises, trade facilitation platforms should be established, and a fairer, more transparent and more convenient business environment for going global should be created for enterprises.

Third, upgrade technology and provide strong support for the digital transformation of export enterprises. On the one hand, under the guidance of digital economy policies and taking innovation as the primary driving force of development, the construction of digital infrastructure and public service platforms should be continuously improved by relying on the comprehensive pilot zones, and support for the research, development and application of digital technologies such as artificial intelligence, big data, cloud computing and blockchain should be increased, so as to provide a better technological environment for the digital transformation of export enterprises. On the other hand, by seizing major opportunities in digital development and building large-scale digital platforms, the agglomeration effect of cross-border e-commerce platforms should be fully leveraged to promote the coordinated development of service resources such as data sharing, logistics and warehousing, cross-border payment, credit evaluation and overseas warehouses, reduce the digital operating costs of export enterprises and improve cross-border trade efficiency. At the same time, in line with international trade rules, the development models and regulatory systems of the comprehensive pilot zones should be continuously innovated, export enterprises should be encouraged to actively carry out digital technology application and business model innovation, and their digital operation capabilities and international market competitiveness should be continuously improved, providing sustained impetus for the high-quality development of export enterprises.

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