

# Study on the urban digital transformation gyroscope model

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## Abstract

**Purpose** – Urban digital transformation has become a key strategy in global countries. This study aims to provide a comprehensive and dynamic exploration of the intrinsic traits associated with urban digital transformation, in order to yield detailed insights that can contribute to the formulation of well-informed decisions and strategies in the field of urban development initiatives.

**Design/methodology/approach** – Through analysis of parallels between urban digital transformation and gyroscope motion in physics, the study developed the urban digital transformation gyroscope model (UDTGM), which comprises of seven core elements. With the balanced panel dataset from 268 cities at and above the prefecture level in China, we validate the dynamic mechanism of this model.

**Findings** – The findings of this study underscore that the collaboration among infrastructure development, knowledge-driven forces and economic operations markedly bolsters the urban digital transformation gyroscope's efficacy.

**Practical implications** – This research introduces a groundbreaking framework for comprehending urban digital transformation, potentially facilitating its balanced and systemic practical implementation.

**Originality/value** – This study pioneers the UDTGM theoretically and verifies the dynamic mechanism of this model with real data.

**Keywords** Urban digital transformation, Gyroscope model, Systemics, Dynamics, Verification

**Paper type** Research paper

## 1. Introduction

As digital technologies, encompassing artificial intelligence, blockchain, cloud computing and big data analysis, continue to advance at a steadfast pace, substantial changes are being witnessed across various sectors, including governance, education, health care, agriculture and aviation. These shifts facilitate the transition of the information-centric society to a multi-dimensionally digitalized one (Dolega *et al.*, 2021; Gordon *et al.*, 2021; Haleem *et al.*, 2022). Cities, as densely populated areas with concentrated economic activities that always generate a larger scale of data, play a crucial role in driving social digital development. So, urban digital transformation with cities as the main focus is of utmost importance.

In recent years, the digital transformation at the urban level has emerged as a new development paradigm for countries around the world. New York initiated the “OneNYC 2050” strategy, accentuating infrastructure enhancement and the integration of avant-garde



technologies to bridge the digital divide, thereby fortifying urban operational systems' safety and reliability. Similarly, London established the London Office of Technology and Innovation in 2019, overseeing collaborations among London boroughs to enhance public services via digital transformation. In China, Shanghai rolled out the "14th Five-Year Plan for Urban Digital Transformation" in 2021, aiming to significantly propel digital momentum, hasten transformative breakthroughs and spur urban growth; Concurrently, Shenzhen unveiled plans within the "Shenzhen Digital Twin Pioneer Urban Construction Action Plan (2023)" to foster a digital twin pioneer city characterized by "digital-reality integration and coexistence, real-time interaction, and second-level response." Additionally, cities such as Tokyo, Seoul and Singapore have prioritized advancing digital transformation aggressively. In this context, the expedited and stable implementation of urban digital transformation has emerged as a central research focus, vital for pursuing sustainable economic and social development (Gomez-Trujillo and Gonzalez-Perez, 2021).

Addressing this theme necessitates first recognizing that urban digital transformation represents a multifaceted, systematic and dynamic endeavor (Teece *et al.*, 1997). Hence, elucidating the dynamic capabilities and strategic management intrinsic to cities, and their collaborative roles in fostering balanced and stable urban digital transformation, is critical in offering precise and proactive guidance or facilitating adjustments.

Through extensive review, existing literature predominantly explores urban digital transformation from two facets: performance assessment (Caird and Hallett, 2019; Guo *et al.*, 2020; Orejon-Sanchez *et al.*, 2022; Zhao *et al.*, 2020) and construction exploration (Anthony, 2021; Hämäläinen, 2020; Hao *et al.*, 2023; Komninos *et al.*, 2022; Qin and Qi, 2021). The former has seen numerous studies undertaking multidimensional analyses to formulate effective evaluation indicators, but the latter primarily uses qualitative approaches to analyze transformation planning and implementation, which lacks quantitative exploration and often exhibits fragmented perspectives, overlooking the systemic and dynamic attributes of cities. In fact, in the research on the performance evaluation of urban digital transformation, it is reasonable to consider many indicators as much as possible to form a perfect evaluation, but as for the research on real-time construction, characteristic engineering is not enough, while the logic of systemics and dynamics really matters (Teece *et al.*, 1997). So, we worked on modeling urban digital transformation dynamically and systematically, which was also expected to be supported by real data. Notably, we observed that some studies have leveraged the "gyroscope model" from physics to depict organizations' dynamic and balanced development, likening the organization to a rotating gyroscope (Cai and Wang, 2022; Usubamatov, 2018). We posited that the functioning of a city mirrors that of a rotating gyroscope, endeavoring to sustain high velocity and equilibrium, influenced by inherent traits and external forces. Therefore, adapting the "gyroscope model" to urban digital transformation research may vividly delineate the operating mechanisms from a systematic and dynamic standpoint, thereby aiding in effectively and promptly steering cities' digital transformation endeavors amidst complex and dynamic landscapes. This spurred our dedication toward the construction and elucidation of the gyroscope model related to urban digital transformation.

In this study, we used a blend of qualitative and quantitative methodologies to better introduce and elucidate the model. Initially, by contrasting the characteristics of the physical gyroscope model with those of urban digital transformation, we devised the urban digital transformation gyroscope model (UDTGM), integrating seven elements: focal point, opportunity and threat plane; rapid strain capacity axis; mechanism structure loop; target-driving force; stable support body; and service display surface. Subsequently, we authenticated the dynamic mechanism of this model using panel data from 268 cities at and

above the prefecture-level in China, encompassing 2412 observations. Our analysis revealed that three principal components – urban infrastructure development, knowledge-driving force and economic development level – synergistically enhance urban digital transformation performance, attesting to the model's effectiveness and interpretability in scrutinizing the dynamic process of urban transformation. Furthermore, heterogeneity analysis indicated varying impacts of different elements on urban digital transformation across diverse regions, offering valuable insights for local governments in tailoring urban digital transformation strategies to local conditions.

This paper's principal contributions manifest in several dimensions. First, it integrates a physical model into urban research, forming the innovative "gyroscope model" of urban digital transformation, which can be called UDTGM, thereby offering fresh theoretical insights for investigating the dynamic and systematic nature of urban digital transformation. Second, by using panel data from Chinese cities, it substantiates the dynamic mechanism of the UDTGM, further enriching the empirical research literature on urban digital transformation dynamics. Third, by conceptualizing cities as dynamic entities, this study vividly elucidates key determinants influencing or propelling urban digital transformation, facilitating cities in executing timely and strategic initiatives to augment transformation performance in alignment with actual scenarios.

## 2. Literature review

### 2.1 About urban digital transformation

The existing research on urban digital transformation is mainly carried out in two aspects – performance evaluation and construction exploration.

*2.1.1 Performance evaluation of urban digital transformation.* Without evaluation to determine the appropriateness, effectiveness and value of programs and projects and their impacts in specific contexts, it is difficult to judge success (Arnold, 2004). Compared with the digital transformation in specific fields such as economy, society and government, urban digital transformation is more systematic and complex. Orejon-Sanchez *et al.* (2022) identified ten evaluation dimensions of smart cities, including governance, urban planning, public management, technology, environment, international outreach, social cohesion, transportation, human capital and economy and set some European cities as references to evaluate the development and implementation of smart cities in Spain. Similarly, Zhao *et al.* (2020) tried to evaluate the level of urban digital economy from the two aspects of internet development and digital financial support (Guo *et al.*, 2020). Through an extensive review of city indexes, Caird and Hallett (2019) identified a wide range of smart urban indicators focused on urban development and urban performance outcomes, applicable across dimensions of governance, society, economy and environment. A challenge for urban indicator frameworks to represent is the complexity of dynamic, evolving, open and unbounded urban systems (Arnold, 2004). Existing research has already made great efforts to evaluate the achievements or effects of urban digital transformation through index exploration, which is important in studying urban digital development and also further used in relevant research (Liu *et al.*, 2022; Wang *et al.*, 2022).

*2.1.2 Construction exploration of urban digital transformation.* With the continuous innovation and diffusion of digital technologies, the rules of urban production and operation are being reshaped. New production relations and production activities are emerging. The construction exploration of urban digital transformation becomes another research hot spot, which is also the focus of this article.

Most work used qualitative methods to discuss how to perform digital transformation in cities. Some of them focused on top-level designing. Hämäläinen (2020) sets frameworks

from four dimensions for a “smart city,” including strategy, technology, governance and stakeholders, facilitating the formulation of digital strategies for cities in relevant dimensions. To address the complexity and system integration challenges faced in digital transformation of cities, Anthony’s study (2021) opted for an enterprise architecture (EA) approach to address the aforementioned issues. In the context of urban development in China, [Qin and Qi \(2021\)](#) reviewed the conceptual definition and practical application of “smart cities,” and concluded that some problems, such as insufficient laws and regulations, information homogeneity and citizen privacy disclosure, ought to be taken into consideration in the planning of urban digital transformation. Some other studies started with the specific cities’ practices, thus analyzing the urban digital transformation mode and path, which can in turn be used to guide practice ([Komninos et al., 2022](#)). [Hao et al. \(2023\)](#) used the fuzzy set method to study the digital transformation practices of key cities across the country, and sorted out the driving factors and constraints of urban digital transformation to understand the differentiated urban digital transformation paths, which may help guide the decision-making of urban digital transformation according to local conditions. Although these studies focused on analyzing the strategies and paths of urban digital transformation, their methods were qualitative and their perspectives were relatively scattered or fragmented.

To summarize, the related work about urban digital transformation mainly focuses on the two aspects of performance evaluation and construction exploration. Regarding the former, existing studies have already made multi-dimensional analysis to form effective evaluation indicators. However, as for the construction of urban digital transformation, most work adopted qualitative methods to discuss the specific planning and implementation, with gaps in quantitative research remaining to be filled. What’s more, the perspectives of this research were scattered, to some extent, ignoring the fact that urban digital transformation is a complex and dynamic system. It is necessary to create a framework for dynamically and systemically analyzing the factors and their collaborative mechanisms in urban digital transformation, to guide or adjust the construction process.

### *2.2 Application of the gyroscope model*

A gyroscope relies on high-speed operation to maintain balance and control changes quickly, which is associated with inertia, precession and the gyro effect ([Usubamatov, 2018](#)). “Gyroscope” can act as a physical model to simulate objects’ rotation and study their gyro effect and is more widely used in engineering design and physical experiments ([Wang et al., 2020](#)). There was also innovative application of the “gyroscope model” in the studies of organization management to solve the problem of the dynamic and balanced development of organizations. In a recent study, the “gyroscope model” was used to analyze the digital transformation strategy of China Merchants Bank ([Cai and Wang, 2022](#)). The five basic elements of the organizational “gyroscope model” are the organization organism; opportunity and threat plane; rapid response ability axis; mechanism structure loop; and target-driving force, which interact to jointly promote the dynamic and balanced development of organizational life. Through the cross-integration of physics and organization management, this research not only revives the gyroscope model in physics, but also makes subjects in organization research more specific and vivid ([Grobman, 2005](#)).

Similar to organizations, cities also need to maintain balance and development under the effects of inner and outside factors, but there is still no extended exploration of the “gyroscope model” in urban studies. We consider that applying the “gyroscope model” from physics to the urban digital transformation study and viewing cities as rotating organisms may help dynamically and systematically understand the digital transformation mechanism

of cities, thus offering a comprehensive perspective to guide the corresponding designing and implementation.

3. Urban digital transformation gyroscope model

3.1 Theory exploration: building the urban digital transformation gyroscope model

The gyroscope principle, characterized by high-speed rotation and balance maintained through external force influence, mirrors the dynamics of urban digital transformation spurred by advancing technologies and growing demand for intelligent services. Much like an open organism, a city must maintain equilibrium amidst various internal and external factors. This makes the gyroscope theory a fitting framework for studying urban digital transformation. Drawing upon the characteristics of both urban digital transformation and the gyroscope model, and inspired by its application in organizational management research, we introduce the UDTGM. This model, detailed in Figure 1, comprises seven interrelated elements that synergistically foster dynamic and balanced growth in urban digital transformation.

In general, the city organism is a “gyroscope,” possessing the “quick-response ability,” standing at the “support point” and rotating on the “opportunity and threat plane,” which is influenced by the target-driving force, mechanism structure loop and stable support body. The real-time rotation effect of the UDTGM is shown on the “service display surface.”

Specifically, data, as a new production factor for industrial development and an important base of urban infrastructure and public service in the digital age, acts as the “support point” of the “gyroscope,” closely related to all elements and links of urban digital transformation. The “opportunity and threat plane” represents the internal and external environment faced by the city organism, to some extent determining the direction and speed of the gyroscope (Gebrihet and Pillay, 2021). The “mechanism structure loop” mainly refers to the economic operation mechanism under the synergy of industries in the digital environment, the external manifestation of which is economic development (Riesener et al., 2019). Because of the reasonable development of the economy, urban digital transformation can be smoother. “Stable

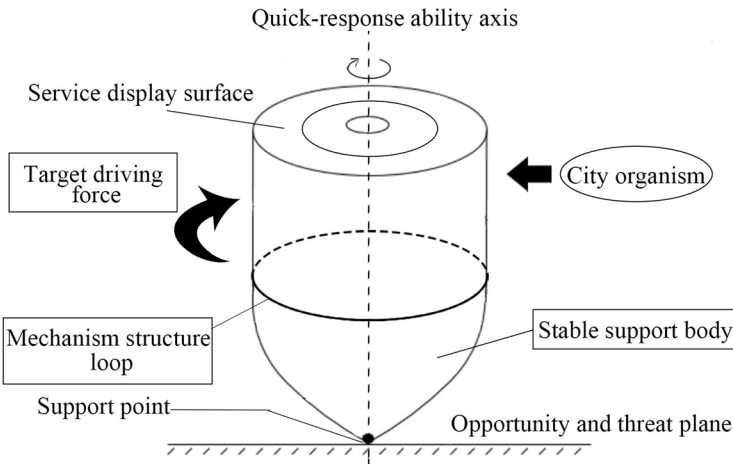


Figure 1.  
Elements of UDTGM

Source: Figure by the authors

support body” refers to the construction of urban infrastructure, which supports the exchange and interconnection of urban data elements, serving as the stable and solid base of urban development (Kamchatova *et al.*, 2021). The “quick-response capability axis” means the competence of cities to respond to external forces. For example, cities can use different strategies to conduct digital transformation according to their judgment of the situation. “Target-driving force” is the force exerted on the cities’ innovation and development. It may be initially generated from the needs of cities’ development in different aspects, such as the economy, government affairs, medical treatment and so on. Ultimately, the results of the city’s digital transformation will be displayed on the “service display surface,” comprehensively reflecting the level of a city’s digital development (Atta and Talamo, 2020).

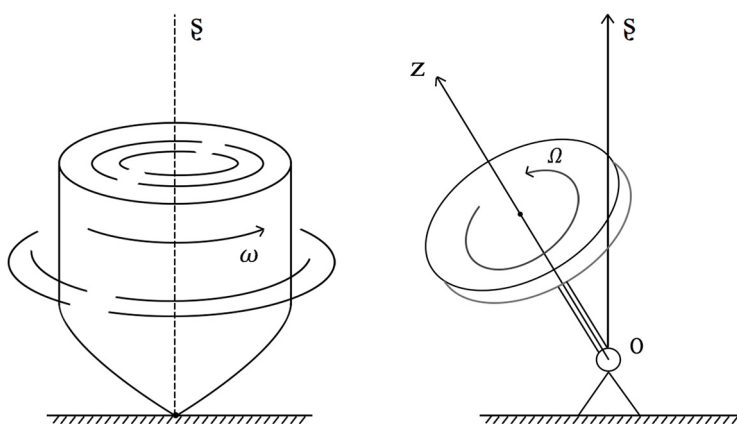
### 3.2 Dynamic mechanism of the urban digital transformation gyroscope model

To further explain the dynamic mechanism of the UDTGM, we introduce the external torque formula of gyroscope rotation in physics, which is defined as the force generated by an object during its operation. The larger the external torque is, the better the rotating effect can be achieved. As is shown in Figure 2, a gyroscope revolves around the central axis  $\xi$  vertical to the ground at an angular velocity  $\omega$ , and it also rotates around its own central axis  $z$  at an angular velocity  $\Omega$  at the same time, which results in its precession motion. According to the “Resal theorem” and gyroscope motion principles (Shatalov, 1986), the total external torque  $M_0$  of the gyroscope can be expressed via formula (1). Besides  $\omega$  and  $\Omega$  mentioned above,  $J_z$ , representing the gyroscope’s moment of inertia, is another factor affecting  $M_0$ .

Furthermore, the angular velocity  $\omega$  is mainly generated by the external force that drives the gyroscope to rotate. The angular velocity  $\Omega$  is highly related to the density of the gyroscope. And the moment of inertia  $J_z$  is largely decided by the weight of the gyroscope itself.

$$M_0 = J_z \omega \times \Omega \quad (1)$$

As for the UDTGM, the external torque represents the effect or performance of the urban digital transformation. The larger the torque, the better the effect of urban digital transformation can be



Source: Figure by the authors

**Figure 2.**  
Generation of a  
gyroscope's external  
torque



obtained. We consider that the moment of inertia ( $J_z$ ), angular velocity of revolution ( $\omega$ ) and angular velocity of rotation ( $\Omega$ ), respectively, correspond to the roles of the stable support body, target-driving force and mechanism structure loop in the model we proposed above. In the following part, we explain the reasons why these factors from our model can fit the external torque formula of gyroscope rotation in physics.

*3.2.1 Moment of inertia of the urban digital transformation gyroscope model.* The moment of inertia of a gyroscope initially represents the support of its inner stability, which is mainly affected by its self-weight. Correspondingly, the moment of inertia of the UDTGM is affected by the weight of the “stable support body,” which can be reflected in the construction of urban infrastructure. Although data is the basic element of digital transformation, it cannot be automatically transformed into productivity directly, whose value cannot be realized without the corresponding data infrastructure, network security system and so on. The urban infrastructure acts as a carrier for urban digital transformation, making data collection, transmission, storage and computing possible.

So, we consider the stable support body made up of urban infrastructure to be a symbol of the inertia moment of UDTGM. In reality, urban infrastructure includes not only the traditional equipment to ensure the smooth progress of urban economic activities and other social activities, but also the new infrastructure driven by technological innovation and aiming at meeting new digital needs. Both traditional and new infrastructure’s construction and updating integratedly do a favor for urban digital transformation.

*3.2.2 Revolution angular velocity of the urban digital transformation gyroscope model.* The revolution angular velocity of a gyroscope refers to the rotational speed generated by the external force around the central axis, which is vertical to the ground. The same UDTGM is generated from the “target-driving force,” which is seen as a knowledge-driving force.

In the process of urban digital transformation, a new generation of information technologies represented by cloud computing, big data, the Internet of Things and artificial intelligence has flourished. New concepts and new technologies are the core competitiveness of cities nowadays. So, we consider the key target of urban digital transformation is knowledge innovation, and the target-driving force is indeed the knowledge-driving force (Mukhametov, 2019).

At the city level, the city government’s investment in education and scientific research plays an important role in promoting the output and dissemination of urban knowledge, which can represent the knowledge-driving force, generate the rotational angular velocity and promote the rotation of the UDTGM.

*3.2.3 Rotational angular velocity of the urban digital transformation gyroscope model.* The self-rotation angular velocity of a gyroscope is related to its precession motion, and is mainly determined by the density of the gyroscope. In the UDTGM, the density of the gyroscope can be explained by the “mechanism structure loop,” which means urban economic operation.

In the digital era, cities’ economic operations may face changes in production relations, which result in the generation of smart agriculture, industrial internet and other production structures in various fields. We consider the economic operation to indicate the long-term developing mechanism of a city, and good economic performance is the guarantee for the health and sustainability of urban digital transformation. So, we regard urban economic operation as the rotational angular velocity of the UDTGM. The better a city’s economic performance is, the more favorable the outcomes of urban digital transformation will be.

## 4. Methodology

### 4.1 Empirical specification

Next, we design our empirical research to verify the dynamic mechanism of the UDTGM. We form our empirical specification based on formula (1). Through mathematical operations, formula (1) can be transformed into a linear regression equation ( $\ln M_0 = \ln J_z + \ln \omega + \ln \Omega$ ), which can equally reveal the relationships between variables and provide convenience for our research. Based on the equation and our research questions about urban digital transformation, a multiple linear regression model is constructed:

$$\begin{aligned} Digi_{it} = & \alpha_0 + \alpha_1 \ln Infra_{it} + \alpha_2 \ln Dri_{it} + \alpha_3 \ln Eco_{it} \\ & + \sum_{j=1}^k \beta_j Controls_{jt} + Fixedeffects + \varepsilon_{it} \end{aligned} \quad (2)$$

In formula (2),  $Digi_{it}$  is the comprehensive digital index of city  $i$  in the  $t$ th year.  $\ln Infra_{it}$ ,  $\ln Dri_{it}$  and  $\ln Eco_{it}$ , respectively, represent the level of urban infrastructure construction, knowledge-driving force and economic operation of city  $i$  in the current year  $t$ . Controls represent the set of control variables and fixed effects represent the fixed effects of the year and the province.  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  are the regression coefficients that this paper mainly focuses on. Next, we import the real panel data of Chinese cities to authenticate the dynamic mechanism of the UDTGM. If the three coefficients are significantly positive, it indicates that the urban infrastructure (“gyroscope moment of inertia”), knowledge-driving force (“gyroscope revolution angular velocity”) and urban economic operation level (“gyroscope rotation angular velocity”) are important factors collaborating to improve the urban digital transformation, and at the same time, the dynamic mechanism of the UDTGM proposed above can also be verified empirically.

### 4.2 Sample selection

Our data sets were extracted from authoritative sources, including the China City Statistical Yearbook (2012–2020), the China Urban Construction Statistical Yearbook (2011–2019) and the Peking University Digital Financial Inclusion Index (Guo *et al.*, 2020). Because of the revision of the China City Statistical Yearbook in 2021, to ensure the coherence of panel data, our sample data consists of cities at and above prefecture level in China from 2011 to 2019. Following the exclusion of city samples that lacked vital data, the research retained a cohort of 268 cities at and above the prefecture level, culminating in a comprehensive compilation of 2,412 city–year balanced panel observations.

### 4.3 Variable measurement

Based on the analysis in Section 3.2, the relationship between the performance of urban digital transformation and three major factors has been explained. Next, we describe their measurement as follows:

**4.3.1 Effects of urban digital transformation.** This paper imitates the practice of Zhao *et al.* (2020) to measure the comprehensive effect of urban digital transformation on two aspects, which are the internet development of the city and the support of relevant financial guarantee facilities. The measurement of internet development at the city level uses four indicators: internet penetration rate, proportion of relevant practitioners, relevant output and mobile phone penetration rate, respectively, calculated by the number of internet broadband access users per 100 people, the proportion of employees in the computer service and software industry in urban units, the total amount of telecommunication services per



capita and the number of telephone users among 100 people. The measurement of digital financial inclusion uses the “Peking University Digital Financial Inclusion Index.” Through the method of principal component analysis, the data from the above five indicators are standardized and then dimension-reduced to obtain the comprehensive index of urban digital development named *Digi*.

**4.3.2 Urban infrastructure construction.** Infrastructure construction is the foundation of urban digital transformation. The area of a built district is always used to describe the area where urban construction and public facilities are basically available in the administrative district of a city. Thus, this paper uses the logarithm of the area of the built district to measure urban infrastructure (*ln Infra*).

**4.3.3 Knowledge-driving force.** The fundamental driving force behind urban digital transformation is knowledge, with talent serving as the vessel for knowledge and education and research being the two main avenues for enhancing the knowledge level of talents and promoting knowledge output and dissemination. This study uses the logarithm of the sum of local government public budget expenditures on education and research to measure the knowledge-driving force (*ln Dri*) in urban digital transformation.

**4.3.4 Economic operation status.** The per capita gross regional product is a primary indicator of the level of economic development in modern cities, reflecting the comprehensive performance of coordinated development across various industries in a city. A higher value of the per capita gross regional product always indicates better economic performance in the city. Therefore, we use the logarithm of the per capita gross regional product to gauge the economic operational state of cities (*ln Eco*).

**4.3.5 Control variables.** Considering the potential influence of other factors on the robustness of empirical results, this study has selected a series of control variables (*Controls*) (Chen *et al.*, 2021; Debeljak and Decman, 2022; Zhao *et al.*, 2020).

Urban scale (C1): Cities serve as the carriers of digital transformation, where an increase in population signifies a heightened demand for digital services, thereby fostering the digital development of the city. This study measures the urban scale using the logarithm of the number of registered residents at the end of the year in the city.

Urbanization level (C2): This is represented by the logarithm of population density.

Human resource level (C3): This is indicated by the logarithm of the number of employees in urban units at the end of the period.

Foreign investment (C4): This is represented by the actual foreign investment used in the year as a proportion of the gross regional product.

Financial development level (C5, C6) (Chen *et al.*, 2021): This study examines both the reservoir (C5) and circulation (C6) states of capital.

The specific definitions, measurement and sources of all variables can be seen in Table 1. Additionally, to control for the possible influences brought about by trends over time and regional policies, this study incorporates year and province effects in the regression analysis.

## 5. Results and discussion

Table 2 shows the descriptive summary and Pearson correlation values for each variable used in this paper. The urban digital development index, denoted as *Digi*, showcases a mean of 0, with a maximum and minimum value of 12.990 and  $-1.742$ , respectively, and the standard deviation is 1.356, indicating that the quality of digital economy development varies greatly among different cities. All the variables are within reasonable ranges.

Table 3 shows the benchmark regression results of this study. As illustrated in Columns (1) to (3), upon incorporating control variables and fixed effects pertaining to time and

**Table 1.**  
Measurement and  
sources of all  
variables

| Type                  | Name            | Measurement                                                                            | Data source                                                                                                   |
|-----------------------|-----------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| Dependent variable    | <i>Digi</i>     | A comprehensive index using the principal component analysis method                    | "China City Statistical Yearbook (2012-2020)"; "Peking University Digital Financial Inclusion Index"          |
| Independent variables | <i>ln Infra</i> | Logarithm of the area of a built district of cities                                    | "China City Statistical Yearbook (2012-2020)" and "China Urban Construction Statistical Yearbook (2011-2019)" |
|                       | <i>ln Dri</i>   | Logarithm of the sum of local government education and scientific research expenditure |                                                                                                               |
|                       | <i>ln Eco</i>   | Logarithm of GDP per capita                                                            |                                                                                                               |
| Control variables     | <i>C1</i>       | The logarithm of a city's year-end registered population                               | "China City Statistical Yearbook (2012-2020)"                                                                 |
|                       | <i>C2</i>       | The logarithm of a city's population density in the year                               |                                                                                                               |
|                       | <i>C3</i>       | The logarithm of the number of employees in urban units at the end of the period       |                                                                                                               |
|                       | <i>C4</i>       | The actual amount of foreign capital used in the year                                  |                                                                                                               |
|                       | <i>C5</i>       | Ratio of deposit balances of financial institutions to GDP                             |                                                                                                               |
|                       | <i>C6</i>       | Ratio of outstanding loans of financial institutions to GDP                            |                                                                                                               |

**Source:** Table by authors

province, urban infrastructure construction level, knowledge-driving force and urban economic operation status, respectively, they exhibit a significantly positive influence on the comprehensive level of urban digital development. In Column (4), integrated into the regression model concurrently, variables' positive impacts on urban digital transformation performance remain notably significant at the 1% level.

The benchmark regression results of our empirical research show that the rotation speed, external driving force and revolving speed of the UDTGM, under the representative of urban digital infrastructure construction, knowledge-driving force and urban economic operation, collaboratively have a positive impact on the rotation effect of the UDTGM. It means that the dynamic mechanism of the UDTGM can be substantiated by real data. Also, the effectiveness of the model in illustrating the complexity and dynamics of urban digital transformation can be further proved.

Table 4 shows the results of the regional heterogeneity analysis. In line with the economic strategy, cities in China can be divided into four economic regions as eastern, central, western and northeastern, whose numbers of observations are 747, 711, 657 and 297, respectively, in our study. The results indicate that within the eastern, central and northeastern regions, factors such as urban infrastructure construction level, knowledge-driving force and economic operations continue to significantly and positively influence the levels of urban digital transformation. In contrast, the western region demonstrates a distinct pattern. While the impact of economic operations remains significantly positive in shaping the digital stature of cities, knowledge-driving forces appear to exert a significantly negative influence on the urban digital level.

**Table 2.**  
Descriptive statistics  
and correlation  
matrix

| Variables       | Digi     | ln Infra | ln Dri    | ln Eco    | C1       | C2       | C3       | C4       | C5       | C6     |
|-----------------|----------|----------|-----------|-----------|----------|----------|----------|----------|----------|--------|
| <i>Digi</i>     | 1        |          |           |           |          |          |          |          |          |        |
| <i>ln Infra</i> | 0.618*** | 1        |           |           |          |          |          |          |          |        |
| <i>ln Dri</i>   | 0.710*** | 0.501*** | 1         |           |          |          |          |          |          |        |
| <i>ln Eco</i>   | 0.705*** | 0.604*** | 0.710***  | 1         |          |          |          |          |          |        |
| <i>C1</i>       | 0.014    | 0.473*** | -0.074*** | -0.095*** | 1        |          |          |          |          |        |
| <i>C2</i>       | 0.273*** | 0.439*** | 0.102***  | 0.201***  | 0.485*** | 1        |          |          |          |        |
| <i>C3</i>       | 0.107*** | 0.265*** | 0.414***  | 0.183***  | 0.137*** | 0.101*** | 1        |          |          |        |
| <i>C4</i>       | 0.468*** | 0.634*** | 0.371***  | 0.492***  | 0.430*** | 0.505*** | 0.093*** | 1        |          |        |
| <i>C5</i>       | 0.149*** | 0.111*** | 0.183***  | -0.272*** | 0.049**  | -0.009   | 0.242*** | -0.007   | 1        |        |
| <i>C6</i>       | 0.261*** | 0.211*** | 0.304***  | -0.116*** | 0.023    | -0.012   | 0.283*** | 0.073*** | 0.843*** | 1      |
| Observations    | 2412     | 2412     | 2412      | 2412      | 2412     | 2412     | 2412     | 2412     | 2412     | 2412   |
| Mean            | 0        | 4.579    | 7.297     | 10.587    | 5.944    | 1.185    | 9.825    | 10.066   | 1.696    | 1.157  |
| SD              | 1.356    | 0.846    | 0.505     | 0.745     | 0.642    | 0.897    | 4.458    | 1.864    | 1.426    | 0.975  |
| Min             | -1.742   | 2.597    | 4.649     | 7.537     | 3.784    | -2.977   | 2.033    | 1.099    | 0.371    | 0.132  |
| Max             | 12.99    | 7.349    | 10.128    | 13.185    | 8.136    | 3.318    | 16.105   | 14.941   | 24.8     | 16.743 |

**Notes:** \*\* and \*\*\* indicate that the correlation coefficient is significant at a level of 5 and 1%, respectively  
**Source:** Table by authors

| Variables       | (1)               | (2)               | (3)               | (4)               |
|-----------------|-------------------|-------------------|-------------------|-------------------|
| <i>ln Infra</i> | 0.534*** (0.036)  |                   |                   | 0.240*** (0.035)  |
| <i>ln Dri</i>   |                   | 1.503*** (0.136)  |                   | 1.102*** (0.060)  |
| <i>ln Eco</i>   |                   |                   | 1.127*** (0.069)  | 0.562*** (0.053)  |
| <i>C1</i>       | −1.229*** (0.036) | −0.535*** (0.066) | −0.312*** (0.075) | −0.213*** (0.051) |
| <i>C2</i>       | 0.100*** (0.028)  | 0.305*** (0.029)  | 0.131*** (0.026)  | 0.191*** (0.025)  |
| <i>C3</i>       | 0.890*** (0.045)  | 0.654*** (0.067)  | 0.475*** (0.078)  | 0.237*** (0.046)  |
| <i>C4</i>       | 0.094*** (0.013)  | 0.044*** (0.015)  | 0.011 (0.013)     | −0.010 (0.012)    |
| <i>C5</i>       | 0.009 (0.020)     | 0.002 (0.027)     | 0.127*** (0.044)  | 0.074*** (0.019)  |
| <i>C6</i>       | 0.175*** (0.031)  | 0.165*** (0.044)  | 0.253*** (0.063)  | 0.190*** (0.028)  |
| Year            | Yes               | Yes               | Yes               | Yes               |
| Province        | Yes               | Yes               | Yes               | Yes               |
| Observations    | 2,412             | 2,412             | 2,412             | 2,412             |
| Adj. $R^2$      | 0.750             | 0.790             | 0.783             | 0.812             |

**Notes:** In brackets are *t*-statistics; \*\*\*, \*\* and \* indicate that the coefficient is significant at a level of 1%, 5% and 10% respectively.  
**Source:** Table by authors

**Table 3.**  
Benchmark  
regression results

| Variables       | (1)<br>Eastern   | (2)<br>Central   | (3)<br>Western    | (4)<br>Northeastern |
|-----------------|------------------|------------------|-------------------|---------------------|
| <i>ln Infra</i> | 0.163** (0.080)  | 0.384*** (0.051) | 0.202*** (0.071)  | 0.194*** (0.043)    |
| <i>ln Dri</i>   | 1.596*** (0.142) | 0.336*** (0.098) | −0.485*** (0.116) | 0.413*** (0.110)    |
| <i>ln Eco</i>   | 0.882*** (0.134) | 0.611*** (0.078) | 0.662*** (0.087)  | 0.600*** (0.091)    |
| <i>C1</i>       | −0.002 (0.134)   | −0.007 (0.060)   | −0.498*** (0.090) | 0.079 (0.094)       |
| <i>C2</i>       | 0.340*** (0.054) | −0.063* (0.036)  | 0.037 (0.034)     | −0.026 (0.064)      |
| <i>C3</i>       | 0.059 (0.120)    | −0.014 (0.044)   | 0.359*** (0.086)  | 0.134 (0.103)       |
| <i>C4</i>       | −0.081** (0.034) | −0.007 (0.020)   | 0.008 (0.015)     | 0.016 (0.022)       |
| <i>C5</i>       | 0.115 (0.104)    | 0.032* (0.018)   | −0.053 (0.061)    | 0.027 (0.022)       |
| <i>C6</i>       | 0.383*** (0.124) | 0.165*** (0.029) | 0.599*** (0.068)  | 0.125*** (0.035)    |
| Year            | Yes              | Yes              | Yes               | Yes                 |
| Province        | Yes              | Yes              | Yes               | Yes                 |
| Observations    | 747              | 711              | 657               | 297                 |
| Adj. $R^2$      | 0.871            | 0.714            | 0.793             | 0.668               |

**Notes:** In brackets are *t*-statistics; \*, \*\* and \*\*\* indicate that the coefficient is significant at a level of 10%, 5% and 1% respectively.  
**Source:** Table by authors

**Table 4.**  
Analysis of regional  
heterogeneity

It is clarified that the effects of different elements on the urban digital transformation differ in different areas. In western regions, the negative influence of knowledge-driving forces on the effect of urban digital transformation may elucidate the ongoing talent attrition phenomenon observed in this region, leading to negative outcomes from investments in urban education and scientific research. This scenario underscores the necessity for urban digital transformation strategies to be intricately woven with localized development conditions. Furthermore, it accentuates the importance of crafting policies that aim to mitigate existing drawbacks while enhancing the inherent strengths of individual cities.

In addition, we make robustness analysis. In our model, economic operation status is assumed to influence the effect of urban digital transformation, but it is also possible that

the level of urban digital development will in turn affect the economic operation, which may derive endogenous problems from the empirical model. And some control variables may also cause such problems. Referencing the research ideas from domestic and abroad, we lag the independent variables for one period, and the results are still significant, proving that the dynamic equation of the UDTGM is robust.

## 6. Theoretical and practical implications

In the digital era, urban digital transformation has become a general strategy in global countries. But how to perform a stable and balanced digital transformation of cities from systemic and dynamic perspectives remains to be solved. This paper combined the principles of physics with urban research to build an UDTGM, aiding in yielding more detailed and logical insights. What's more, with the balanced panel data of 2,412 observations from 268 cities at and above the prefecture level in China, the dynamic mechanism of the UDTGM was verified empirically.

This study both enriches theoretical and empirical insights for investigating the dynamic and systematic nature of urban digital transformation. Theoretically, with the proposal of the UDTGM, a city is treated as a dynamic organism, making it easy to understand and capture the changes of conditional factors influencing the urban digital transformation. Seeing a city as a rotating "gyroscope," we can explore how it can sustain high velocity and equilibrium from the aspects of "focal point," "opportunity and threat plane," "rapid strain capacity axis," "mechanism structure loop," "target-driving force," "stable support body" and "service display surface" in real contexts. The utilization of UDTGM is meaningful for dynamically and comprehensively understanding and analyzing urban digital transformation.

Based on the empirical results, some practical advice about urban digital transformation is also achieved, as follows.

First, place importance on infrastructure development. Like a gyroscope's stable support body, infrastructure serves as the backbone of urban digital transformation. Improving and optimizing infrastructure is conducive to the sustained enhancement of digital transformation levels.

Second, value the cultivation and recruitment of talents. As the carriers of knowledge, talents generate the continuous knowledge-driving force. Emphasizing the basic and professional talents' cultivation, supports the city in building up its innovation and scientific research capabilities, which improve the plasticity and toughness of cities in digital transformation.

Third, adjust the industrial structure in the digital environment and maintain robust economic development. The functioning of the economy reflects the long-term developmental mechanism of a city, and robust economic performance is crucial for ensuring the vitality and long-term viability of urban digital transformation.

Forth, maintain systematic and dynamic thinking. The rotation of UDTGM is not a simple cycle repeat but contains complexity and dynamism. Monitoring the changes of conditional factors influencing the urban digital transformation systemically and dynamically really matters in making timely decisions and guides.

## 7. Limitations and future directions

The limitation of this article lies in two points. First, based on the dynamic formula, the verification of the dynamic mechanism of the UDTGM only involves three elements of this model. The working mechanisms of other elements still lack further empirical verification.

Second, our samples are Chinese cities, without verifying the empirical effectiveness of the model with data from cities in different countries.

In the future, we will consider these two limitations and improve the explanation and application of the model. In addition, as a city is a complex system, urban digital transformation often involves collaboration among various stakeholders, including government, businesses, academia and communities. We will further explore the coordinated evolutionary relationships between the digital transformation of cities and stakeholders.

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