

Article

Disruptive Innovation Patterns Driven by Mega-Projects: A Sustainable Development Pattern Case of China's High-Speed Rail

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Abstract: Sustainable development of mega-projects has drawn many concerns around the world. The theory of disruptive innovation in mega-projects is a typical sustainable development pattern but still lacks systematic understanding. This article takes China's high-speed rail (CHSR) project as an example to analyze the disruptive innovation pattern of mega-projects. First, this paper systematically traces the theories of disruptive innovation and summarizes the connotations of disruptive innovation. Simultaneously, from the historical development of several typical mega-projects in China, this paper summarizes the connotations of mega-projects. Based on two connotations, this paper summarizes the theoretical basis of disruptive innovation in mega-projects. Second, this paper takes the CHSR project as a case to analyze its innovation pattern from the analysis of the development process, operation mechanism and influence in sustainability; the disruptive innovation pattern is put forward afterward. Third, the discussion is drawn from the perspectives of the characteristics, scope of application and innovation environment of the disruptive innovation of CHSR. Last, the conclusions of this article are summarized.

Keywords: mega-projects; China's high-speed rail; disruptive innovation; sustainable management pattern; innovative elements

1. Introduction

The sustainable development of mega-projects is a very significant part of the sustainable development of economy and society. The pattern innovation of mega-projects is a paradigm shift in the sustainable development of mega-projects [1,2]. Despite having a strong influence, theories of sustainable development of projects have not paid much attention to the pattern research [3–5]. The earliest research on innovation originated in Schumpeter's book [6], and Schumpeter argues that the introduction of "new combinations" of production factors and production conditions into production systems is an innovation. Freeman [7] summarizes the essence of technological innovation as "the first commercial transformation of new products, new processes, new systems and services." Ettlie [8], Dewar [9] and Nord [10] divide innovation into radical and incremental innovation. When Freeman [11] studied in the Science Policy Research Unit of the University of Sussex in the United Kingdom, he divided innovation into incremental innovation, radical innovation, change of technology system and change in the techno-economic paradigm based on the degree of innovation.

Since Abernathy [12] proposed the concept of disruptiveness in 1985, Christensen, a scholar at Harvard University in the United States, explained the concept of disruptive technology further and systematically analyzed this concept in his book "The Innovator's Dilemma" [13]. He pointed out

that disruptive technology originated in a low-end, non-mainstream product or service designed for a new breed of customers. Compared with the existing company's products [14], the company made a revolutionary outbreak in the process of production or operation. With the continued improvement on technical performance, it finally disrupted the mainstream market and completed the replacement. Since then, research on disruptive innovation in industry and academia has gradually become a hot topic. Some research results have gradually become the guidelines for entrepreneurs to run their own businesses. This includes the forecasting methods of disruptive technologies [15], the different application strategies to disruptive technologies among different enterprises with different sizes [16], and the criteria that judges the degree of technology disruption [10]. Some advanced enterprises even require that their enterprises can identify potential disruptive technologies to cope with the impact they have on the industry when they face disruptive technologies. While most businesses are aware of these technologies before new technologies can make a disruptive outbreak, they cannot foresee how much of those technologies will be able to develop and how much of the industry's existing technology will be replaced. For example, the disruptive development of hard disk drives [8] is beyond the expectations of many corporate decision makers. For managers in mature industries, they do not expect development and diffusion of disruptive technologies [17], because [8] in mature markets, incumbent products and technologies occupy the mainstream of the market, the fixed assets and production processes, when operating habits are relatively stable, while new products use new competitive design or methods, when replacing the original mature products. Companies must face high prices to update equipment, trainers, and to compete with new rivals, which often causes significant sunk costs. Meanwhile, managers often cannot predict the destructive potential of disruptive technologies because their perception of the industry is often hampered by perceptions of existing technologies [18], while others [9,19–22] believe that the reasons are a lack of staff training, and an inadequate investment in innovation and technical management that tends to hinder the pace with which enterprises cope with disruptive technologies. However, from another perspective [23], disruptive technologies are not completely isolated from the existing technologies—they can be combined with existing technologies by transforming existing products and creating entirely new products. Therefore, with a positive attitude to face the disruptive technologies, learning to understand the characteristics of disruptive technologies can become a universal understanding of business managers.

The first research on disruptive innovation in China occurred in 2001. After that, Dai Yongping [24] proposed that the OLED screen had the potential to become a disruptive technology. This technology was adopted in the screen of Apple's new flagship mobile iPhone X in 2017—it has gradually become a disruptive technology that was successfully predicted. Subsequently, research about disruptive innovations in China included the identification of disruptive technologies [25], the analysis of the evolution of disruptive technologies [26], disruptive technology analysis methods [27], disruptive innovation mechanisms [28–30], disruptive innovation patterns [31], and industry disruptive innovations [32]. As for research dimensions of disruptive innovation, existing research includes the technical dimension (3D printing technology [32]), change of technology system (cloud computing [33]; digital currency [34]), change in techno-economic paradigm (Shared Economy [35]).

The research on disruptive innovation based on the background of mega-projects is not enough. Only Feng Ling [36] analyzed China High-Speed Rail (CHSR) from the perspective of developing a path of disruptive innovation. The reasons for this are as follows: first, scholars did not break through the traditional concept of Christensen's subversive concept that "disruptive technologies are based on market competition and occur more in the innovation activities of small enterprises", ignoring the fact that the government's "visible hand" plays an important decisive role in the development of mega-projects that are under the influence of large enterprises and enterprise groups; second, when studying predecessors' research about mega-projects, researchers focus more on organizational collaborative innovation [37,38], integrated innovation and management pattern innovation, etc., and ignore the research on the characteristics of innovation activities. These are the two reasons for the research deficiency on disruptive innovation in mega-projects. The research in this paper is based

on the concept that disruptive innovation of mega-projects is led by the government, to provide a theoretical base of research in the field of disruptive innovation.

2. Materials and Methods

2.1. Materials

Our research materials in this paper include state statistical data, interview information, and railway industry data. Correspondingly, we use the statistical data from the China National Bureau of Statistics, the high-speed rail yearbook of China, and the railway industry survey data to analyze and describe the development process of CHSR (see Section 4.1). We used the interview information of experts from the Academy of Railway Sciences and literature reports to refine the operating mechanism of CHSR (see Section 4.2). We used high-speed railways, highways and aviation traffic data, and environmental data to compare and analyze the contribution of the high-speed rail in promoting the sustainable development of China. We also use regional urban GDP data along the Beijing-Shanghai high-speed rail line from 2008–2013 to analyze the impact of the construction and operation of the high-speed rail on the sustainable development of the regional economy.

2.2. Methods

We used the literature survey method to summarize the different connotations of disruptive technologies (see Section 3.1). The material survey method was used to analyze the similarities and differences in the innovation process for several representative mega-projects in China (see Section 3.2). We synthesized the connotations of different types of disruptive technologies and proposed the connotations of disruptive innovation driven by mega-projects (see Section 3.3). Based on case study and data comparison methods, we analyzed the disruptive innovation pattern of CHSR (see Section 4).

In the case study section, we used the Difference-In-Difference (DID) model to analyze the changes of GDP growth for the cities along the Beijing-Shanghai high-speed rail line and compared the impact of CHSR on the sustainable development of economic growth. The DID model is a measurement method used in recent years to quantitatively evaluate the effect of project implementation. The model was first introduced by Card and Ashenfelter in 1985 [39] and has since been widely used in econometrics and quantitative research in the social sciences.

The design of the DID model:

$$y_{ist} = \gamma_s + \lambda_t + \delta D_{st} + \varepsilon_{ist} \quad (1)$$

y_{ist} is the dependent variable for i , s stands for a city, t stands for time. γ_s and λ_t the vertical intercepts for s and t respectively, D_{st} is a dummy variable for treatment status, δ is the treatment effect, and ε_{ist} is an error term.

Respectively:

$$\bar{y}_{st} = \frac{1}{n} \sum_{i=1}^n y_{ist} \quad (2)$$

$$\bar{\gamma}_t = \frac{1}{n} \sum_{i=1}^n \gamma_s = \gamma_s \quad (3)$$

$$\bar{\lambda}_t = \frac{1}{n} \sum_{i=1}^n \lambda_t = \lambda_t \quad (4)$$

$$\bar{D}_{st} = \frac{1}{n} \sum_{i=1}^n D_{st} = D_{st} \quad (5)$$

$$\bar{\varepsilon}_{st} = \frac{1}{n} \sum_{i=1}^n \varepsilon_{ist} \quad (6)$$

When $s = 1, 2$ and $t = 1, 2$, then

$$\begin{aligned} & (\bar{y}_{11} - \bar{y}_{12}) - (\bar{y}_{21} - \bar{y}_{22}) \\ &= [(\gamma_1 + \lambda_1 + \delta D_{11} + \bar{\varepsilon}_{11}) - (\gamma_1 + \lambda_1 + \delta D_{12} + \bar{\varepsilon}_{12})] - [(\gamma_2 + \lambda_1 + \delta D_{21} + \bar{\varepsilon}_{21}) - (\gamma_2 + \lambda_1 + \delta D_{22} + \bar{\varepsilon}_{22})] \quad (7) \\ &= \delta(D_{11} - D_{12}) + \delta(D_{22} - D_{21}) + \bar{\varepsilon}_{11} - \bar{\varepsilon}_{12} + \bar{\varepsilon}_{22} - \bar{\varepsilon}_{21} \end{aligned}$$

Then,

$$E[(\bar{y}_{11} - \bar{y}_{12}) - (\bar{y}_{21} - \bar{y}_{22})] = \delta(D_{11} - D_{12}) + \delta(D_{22} - D_{21}) \quad (8)$$

Generally, assume that $D_{22} = 1$ and $D_{11} = D_{12} = D_{21} = 0$, and the treatment effect is given as

$$\hat{\delta} = (\bar{y}_{11} - \bar{y}_{12}) - (\bar{y}_{21} - \bar{y}_{22}) \quad (9)$$

The illustration of DID is shown in Figure 1.

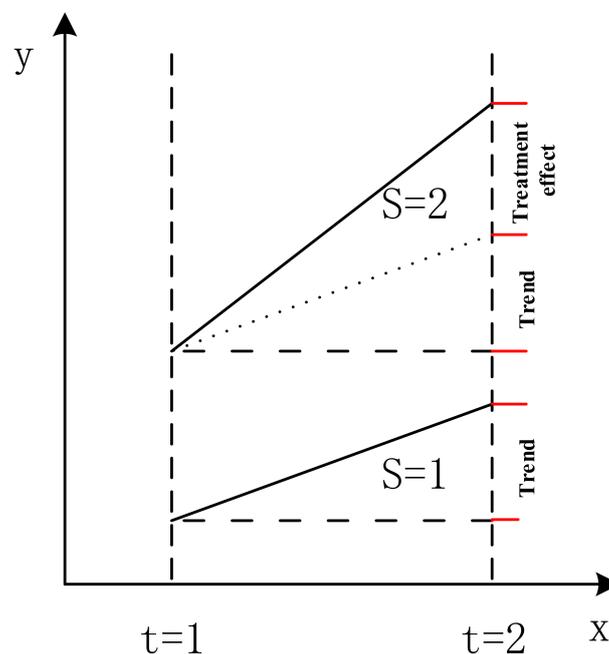


Figure 1. The illustration of the DID model.

The project effect could be measured by comparing the treatment effect δ before and after the implementation of the project. Generally, when δ is a positive number, the project usually has a positive effect.

3. Connotation of Disruptive Innovation Driven by Mega-Projects

As we have mentioned above, the existing studies on disruptive innovation focus more on innovation activities of SMEs. Based on the analysis of the connotation of the disruptive technology and the connotation of mega-projects, we constructed the theoretical connotation of disruptive innovation driven by mega-projects and regarded it as the theoretical basis of this study.

3.1. Connotation of Disruptive Technology

The original explanation for disruptive technology [11,12] was a marginal low-end new product or service designed for a new group of customers, with continuous improvement on its performance or function, gradually and ultimately replacing the incumbent products or services. After that, with the deepening of research, the explanation of disruptive technology has gradually expanded beyond the original one. Some examples are explanations in national defense fields [40], military fields [41] and

engineering fields [42], which has gradually jumped out of the category of marginal low-end objects in the commercial field. We summarized the connotation of disruptive technologies into four kinds.

1. Christensen's connotation.
2. The exploding trait of disruptive.
3. The dominant force is driven by the market.
4. The degree and effect of disruptive.

We explain them below.

Based on Christensen's connotation. Christensen first systematically introduced the concepts of disruptive technologies. Later, the connotations were refined and developed by Danneels [42] and Tellis [43], who commented on the advantages and disadvantages of this concept, noting that disruptive technologies were first introduced in the low-end, non-mainstream market, but have the potential to steadily upgrade to be a dominant technology. They define the initial characteristics of disruptive technologies as low-cost, small, simple, easy to use, low mainstream market adoption. Danneels [42] also defines disruptive technology as a technology that changes the basis of business competition. It is different from the characteristics of continuous technology. Huang [23] considers the technology that provides products relatively low in initial performance but can seize the emerging markets from dominant technology that is not covered of, and continue to erode the market share of incumbent technology as a disruptive technology. These definitions of disruptive technology are basically similar to that of Christensen's.

Based on the exploding trait of disruptive. Disruptive technologies do not follow the performance improvement track of sustainable technologies but replace the existing technologies by changing the technical performance track. Anderson [44] argues that disruptive technology will break the original technology track, interrupt the original technology life cycle and form a new technological track. Christensen [11] also argues that the emergence of new technical attributes can lead to a shift in the way the technical performance improves, resulting in disruptive technologies. In 2013, the U.S. Department of Defense defined disruptive military technology as "a group of technologies that solve problems in a way that quickly breaks down the balance of power between their opponents." [45] These opinions are based on the exploding trait of disruptive.

Based on the dominant force is driven by the market. In terms of technological competitiveness, Danneels [42] argued that the key to defining disruptive technologies is that under the market, such technologies can underpin changes in the competitiveness of firms. Walsh [46] analyzed different types of coping strategies and conditions based on the definition that disruptive technologies are different in different market segments.

Based on the degree and effect of disruptive. An Wang [15] divided disruptive innovation into three kinds based on the degree of disruptive.

1. Original innovations based on new principles and discoveries.
2. Integrated innovations and applications based on existing technologies.
3. Transfer innovations based on new scientific theories and mature technologies.

Slavin, KV [47] divides disruptive technologies into successful and unsuccessful disruptive technologies, arguing that successful disruptive technologies will bring a revolutionary outbreak to the industry, while unsuccessful disruptive technologies will gradually disappear and be forgotten by people. This view also raises the debate on whether disruptive technologies must succeed.

3.2. Connotation of Mega-Projects

Mega-projects have overall fundamental and revolutionary influence on economic and social development. They also have large-scale investments with long periods and high coordination difficulties. They often involve the interaction between the government and the market, and the

government is a very important driving force. In China, the leading force of the major mega-project has undergone a shift from “government-implemented” to “government-implemented + market-involved” and then to “government and market implemented.” From the founding of the People’s Republic of China to the beginning of the reform and opening policy (1949–1978), China implemented the planned economic system. The mega-projects are purely “government-implemented” because there are no mature and substantial enterprises in China, the most powerful research institutions are state-owned. The “two bombs and one satellite” (atomic bomb, guided bombs, man-made satellite) project adopted this model. After that, the research institutions have switched from state-owned to commercial enterprises. However, in the early stage of the transition, commercial enterprises have limited capabilities, forming a “government-implemented + market-involved” management model. This model has been adopted by China’s “manned spaceflight” project. In the 21st century, the technological innovation capability of commercial enterprises has been significantly strengthened. Under these circumstances, mega-projects implemented by national organizations and commercial enterprises gradually formed a “government and market implemented” management model. The high-speed rail project is one of the typical representatives. Representative mega-projects and the evolution of the driving force is shown in Figure 2.

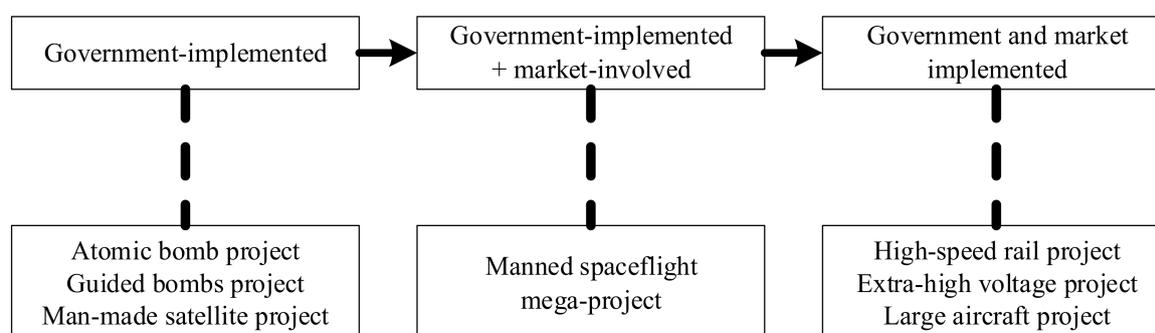


Figure 2. Representative mega-projects and the evolution of the driving force.

3.3. Connotation of Disruptive Innovation Driven by Mega-Projects

Innovation processes of several mega-projects in China undergo three different innovation periods, from independent innovation to Introduction + Digestion + Absorption + Re-innovation (IDAR innovation [36]) and then to integrated innovation. As the name implies, independent innovation is mainly based on the primitive self-accumulation, while the IDAR innovation is based on the absorption of foreign advanced technologies. Integrated innovation is the coupling of complex technical systems. In addition, since the founding of the People’s Republic of China, most mega-projects have had a weak start-point. The comparison with the international advanced technologies is also regarded as an important factor for measuring the innovation success degree of mega-projects. From the historical analysis of the development of several mega-projects, the high-speed rail project and extra-high voltage project are large-scale application-oriented mega-projects with a vast market. Their innovation processes have gone through three entire types of innovation processes (from independent to IDAR to integrated innovation) and reached the leading position in the world. Compared to them, the “two bombs and one satellite” mega-project and “manned spaceflight” mega-project rely on independent innovation and integrated innovation, which have little cooperation with other countries and lack IDAR process. These two projects have not reached a leading position in the world yet. Another type of project is the “large aircraft” project, which, like the high-speed rail project and extra-high voltage project, has gone through three entire types of innovation processes but is still in the stage of catch-up. This is mainly because the initial time of “large aircraft” is located in the 21st century. Compared to these five mega-projects, we believe that the innovation of projects that has

reached the leading position of the world is more likely to be a typical disruptive innovation. Figure 3 depicts the typical degree and process of disruptive mega-projects with a two-dimensional view.

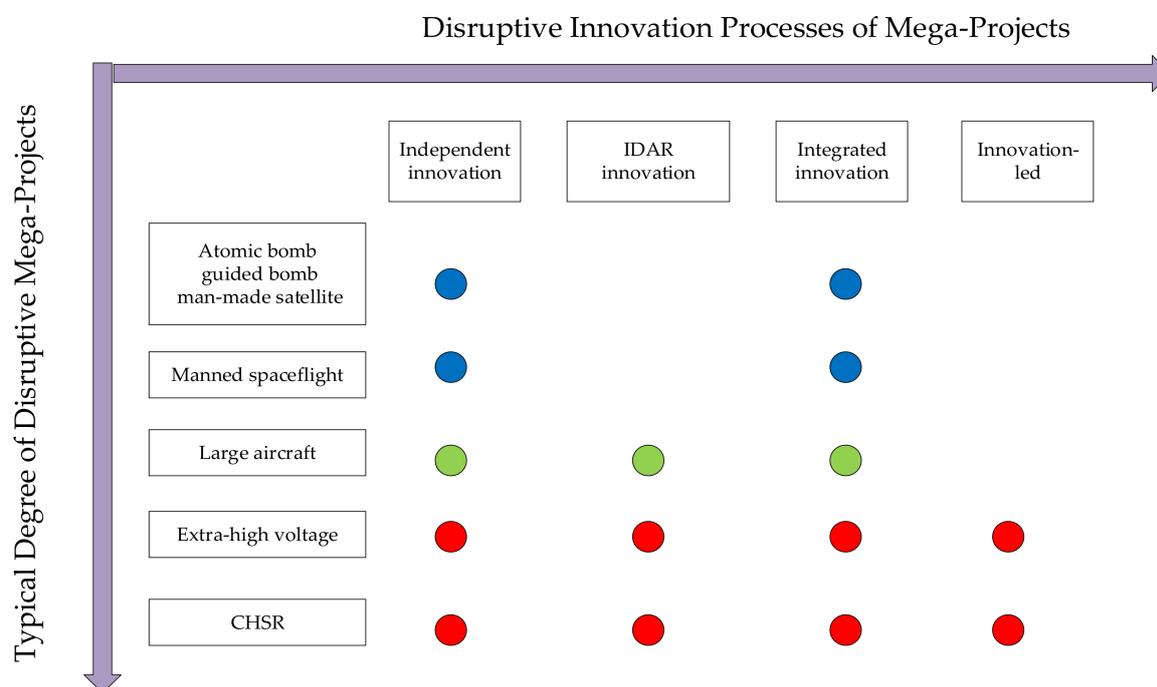


Figure 3. Disruptive innovation process of different mega-projects.

In this paper, we show that the connotation of disruptive innovation is a broader concept of disruptive technology. We not only analyzed the concept of technology, but also analyzed border objects such as scientific principles, technical systems, and technical and economic paradigms. Also, its driving force can be market driven, while government or oligopoly could also be the main driving force.

Thus, based on the connotation of disruptive innovation and mega-projects, we tagged disruptive innovation driven by mega-projects with several labels.

1. The project has fundamental and global influence on economic and social development in one country.
2. Government or large oligarchs constitute the main implemental forces.
3. Undergo independent to IDAR to integrated innovation processes and reached the leading position of the world.
4. Accomplish these processes in a relatively short time and bring sustainable contributions to the development of economy and society.

4. Case: CHSR's Innovation Pattern

How is CHSR disruptive innovation pattern reflected? We will analyze it in detail by analyzing the development process, operation mechanism and the contributions of the high-speed rail in promoting sustainable development in China.

4.1. Development Process of CHSR

4.1.1. Technological Level

The technological development of CHSR has undergone a “chase-parallel-lead” process compared to others. The overall technological level has reached the leading position of the world [36,48].

The historical development of the foreign high-speed rail originated in Japan. The world's first high-speed rail, Shinkansen, was built in 1964—the operational speed was 200 km/h. Then the world's high-speed rail's technological level developed steadily. In 1981, the French built the first European high-speed rail with the operational speed at 270 km/h. In 1991, Germany fulfilled the first ICE high-speed rail line with the operational speed at 250 km/h. Afterwards, Spain, South Korea, Taiwan, and other countries and regions also began to build high-speed rail projects. Taking the operating speed as criteria, most high-speed rails have reached a 300 km/h operational speed, a few have reached 320 km/h, which represents the highest level of technology. This process can be depicted by the black line in Figure 4.

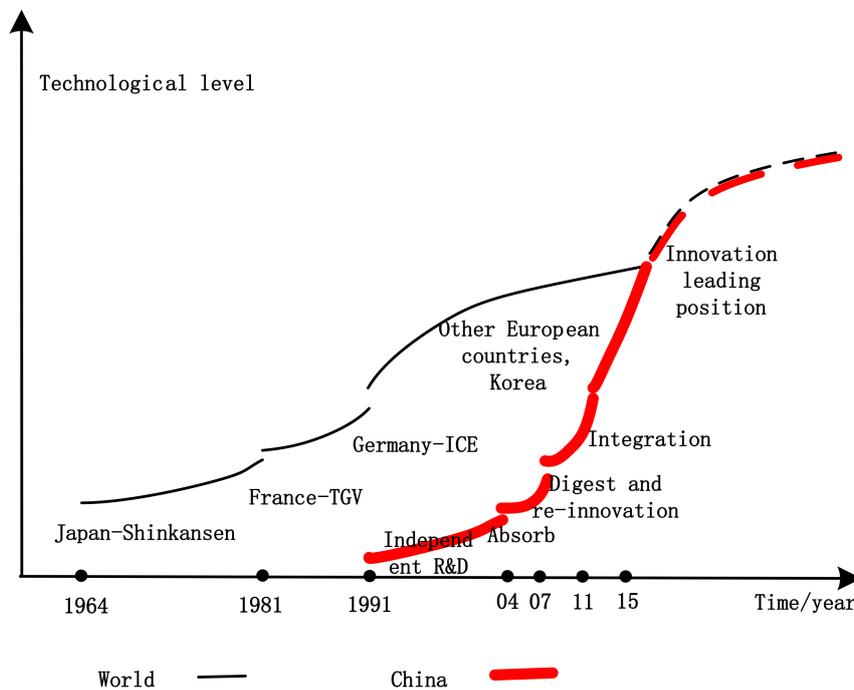


Figure 4. High-speed rail technological level comparison between world and China.

In comparison, the development of CHSR started in the 1990s; the initial R&D was independent. In January 2004, the government approved “Medium and Long-term Railway Network Planning” to determine if the rail network should expand its scale and build a “four vertical and four horizontal” high-speed rail network. Since then, CHSR began to absorb large-scale foreign advanced technologies and accomplish local digestions with technological upgrading. In 2007, the first high-speed rail train began to run in China at a 200 km/h speed. In 2011, the high-speed rail line gradually shaped into a network, the operational speed reached 300 km/h and the testing speed reached 497.3 km/h. In 2015, China created a new generational high-speed rail train “CRH400” that was designed independently; the design speed also reached the top of the world. The overall technological standard has gradually reached the leading position in the world. This process shown through the red line in Figure 4.

Comparing the red line and the black line in Figure 4, we can see that CHSR has surpassed similar projects in developed countries in terms of development speed and technological level in a shorter time. It can be determined that China's high-speed rail has reached the world's leading level on the technological level represented by its operating speed.

4.1.2. Railway Networks

Based on the dimension of the railway network, the operation of the high-speed rail in China has revealed a rapid and wide-range development. The expansion of CHSR's construction and operation

is very fast. Since the opening of the Beijing-Tianjin line in 2007, 21,700 km of high-speed rail lines have been completed and put into operation by the end of 2016 (see Figure 5). Occupying more than 60% of the world's actual high-speed railway mileage, CHSR is developing much faster than high-speed rails in developed countries in history. In addition, the “Medium and Long-term Railway Network Plan” approved in 2017 further expands the construction scale of the high-speed rail in China and proposes an “eight vertical and eight horizontal” high speed rail network with a total planned size of 38,000 km in 2030.

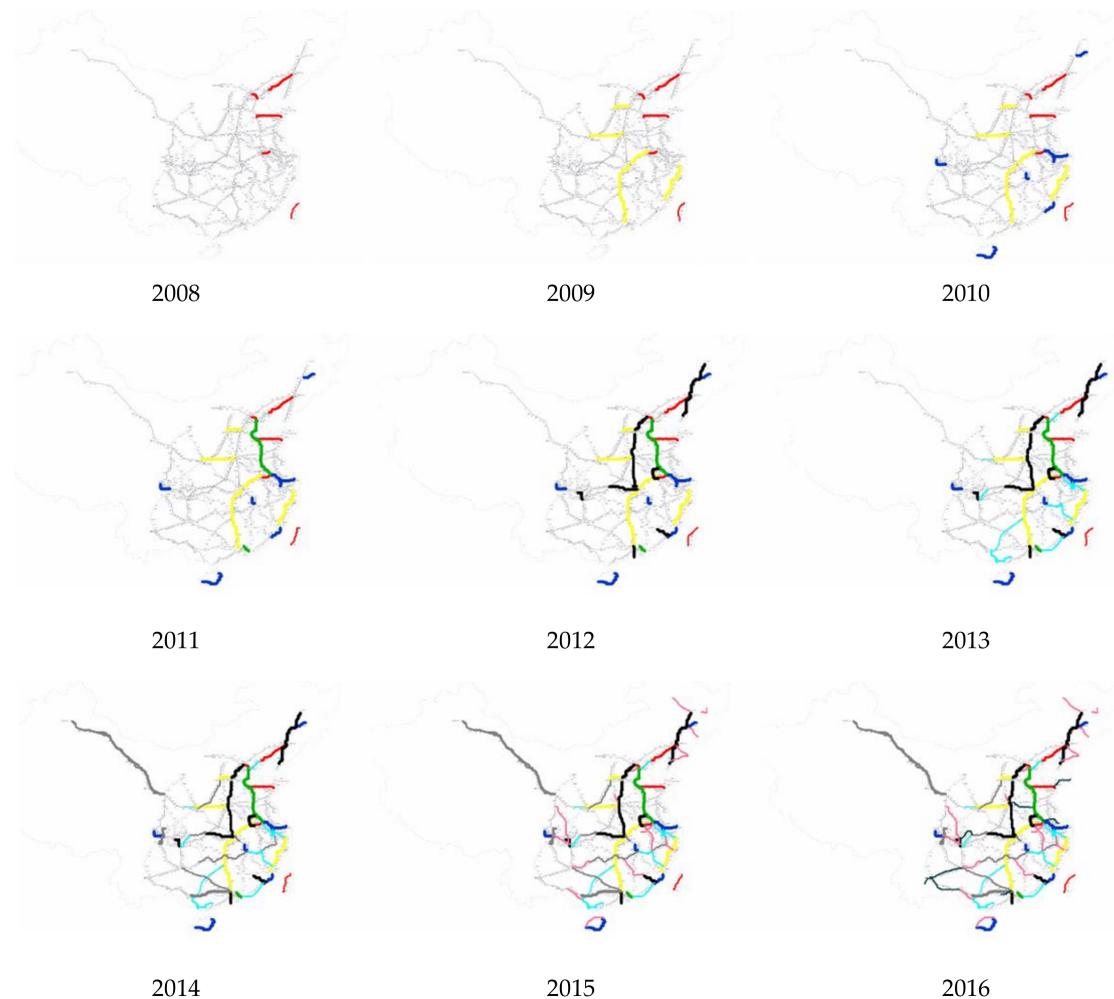


Figure 5. Dynamic development of CHSR. Source: The author organizes data according to the China Statistical Yearbook and relevant network information. Note: Different colored lines represent high-speed rail lines that have operated in different years. Respectively, the colors represented in 2008–2016 are red, yellow, blue, green, black, cyan, dark gray, pink, and dark green. In addition, the dark gray background lines are the planned high-speed rail networks for 2020.

4.1.3. Industry Division

Based on the dimension of the industry division, the system integration of CHSR is extremely difficult.

The industry of CHSR is roughly divided into five major sections; the operation segment, equipment manufacturing segment, communication signals segment, project construction segment, and research segment. The industrial structure of each segment is dominated by mainly oligarchs, while the technical independence among segments is high. The China Railway Corporation is the oligarch in the operation segment; its main work is passenger and freight transport services, railway investment, and construction plans. The China Railway Rolling Stock Corporation (CRRC) is the

largest oligarch in the equipment manufacturing segment, it is responsible for the manufacture of railway equipment. The China Railway Communication Signal Corporation is the largest oligarch in the communication signals segment. It basically controls the major business of this industry. The China Railway Engineering Corporation (CREC) and the China Railway Construction Corporation (CRCC) are two major oligarchs in the project construction segment. In addition, universities, research institutions, and other research and development units form the research segment. The division of the high-speed rail industry is dispersive and requires extremely high industry integration. Innovation activities of CHSR are not simple technological innovations, but also contain many aspects of system, organization, and market innovation.

Monopoly, in general, often means low efficiency. However, the industry monopoly of CHSR is also the main reason for the success of CHSR. The monopoly under a government-led organization is more conducive to the smooth development of high-speed rail projects that with large investments and high difficulty in organization and coordination. However, with the development over time, the operation of the high-speed rail needs to introduce more market competition mechanisms to improve the service level and profitability. The market reform in CHSR's system in recent years reflects this development trend.

4.1.4. Leading Position of CHSR

Based on the above three-dimensional analysis, it can be determined that the development of CHSR is of a high quality, fast speed, wide range, and difficult industrial integration, which exceeds the general complexity circumstance of industrial development. The leading position of CHSR is not only leading in terms of technology, but also in the network scale, operational speed, and cost control. This data is shown in Table 1.

Table 1. Comparison of International High-Speed Rail.

Countries	Network Scale in 2016 (km)	Highest Operational Speed in 2017 (km/h)	Ticket Prices (yuan/km × person)
China	21,719	350	0.32
Japan	3041	300	1.71
Germany	1475	300	1.21
France	2142	320	1.02
Spain	2871	300	1.25

Sources: The network scale collected from the World Bank. Different definitions of a high-speed rail results in different data. Operational speed and ticket prices were collected from the "China Rail Transport Industry Development Report 2017."

As we can see from Table 1, CHSR has the largest high-speed rail network compared to other main countries. It also has the highest operational speed and the lowest ticket prices. In addition, from the characteristics of the innovation process of several mega-projects in different periods (see Figure 3), the innovation and development of CHSR also covers the three major processes of disruptive innovation, which includes independent innovation, IDAR innovation, integrated innovation. It also ultimately reached a leading position in the world in terms of some aspects. It is a typical disruptive innovation driven by a mega-project.

4.2. Operation Mechanism of CHSR

4.2.1. Implementation Subjects

The government, enterprises, and research institutions are the three main implementation subjects of the disruptive innovation of CHSR. "Government-lead + enterprise-dominant + research institution-support" is its typical characteristic. The government designed the development target of CHSR and put forward industrial policies, project guidance and market access standards.

The enterprises play a dominant role in technology digestion, upgrading, trial-innovation and development. Research institutions have great contributions to the innovation of relevant theories, human resource cultivation, and research works. The three implementation subjects are combined organically to facilitate the disruptive innovation and development of CHSR.

4.2.2. Dominant Factors

Policy, capital, and human resources are the three dominant factors of disruptive innovation in CHSR [48,49]. “Policy guide + capital support + human resources guarantee” is its typical characteristics. In the innovation and development of CHSR, the government’s policies established the development direction, path, and environment of CHSR. Capital support R&D projects, absorb the enterprises to actively participate in the project construction. Human resources from enterprises and institutions provide a knowledge and technology creation resources for CHSR. All these three dominant factors guarantee the disruptive innovation and development of CHSR.

4.2.3. Outbreaks

Similar to the outbreaks of general disruptive innovations, the disruptive innovation of CHSR have three outbreaks: practical outbreak, mass production outbreak, and mainstreaming outbreak. The high-speed rail train imitating production from other countries is the practical outbreak, which means technologies have been roughly learned. The product assembly line beginning to work domestically is the mass production outbreak, which means enterprises have a deeper understanding of such technologies. The new generation of the Chinese standard EMU completed is the mainstreaming outbreak, which means enterprises have comprehensively grasped all technologies and have their own innovations. The three outbreaks are the key nodes for the continuous improvement of the quality of CHSR.

4.3. Influence of CHSR in Sustainability

The contribution of CHSR in sustainable development is analyzed from the following perspectives. We used the distance of 800 km as an example and compared high-speed rails with highways and civil aviation to illustrate sustainability of the transportation system. We use the regional GDP data and DID model to illustrate the impact of CHSR on the sustainable development of the economic growth. We also used the converted greenhouse gas emission data to illustrate the environmental influence of CHSR.

4.3.1. Transportation Efficiency

A comparative analysis of the high-speed rail, highway, and civil aviation was conducted to analyze the influence of CHSR on its sustainability for transportation efficiency. Specific indicators include travel expense, travel time, traffic volume, fatal accidental rate, and travel on-time rate. Among them, the lower the travel expense, the more sustainable it is. Travel time is 800 km travel time plus necessary preparation time. The shorter the time, the more sustainable it is. The traffic volume is the number from the average annual passenger carrying capacity, and the greater the carrying capacity, the more sustainable it is. Fatal accidental rate is an important indicator of safety. The lower the rate is, the more sustainable it is. In addition, the higher the travel on-time rate, the more reliable and more sustainable it is (see Table 2).

Table 2. Indicators Comparison of Transport Efficiency.

Traffic Tools	High-Speed Rail	Car	Plane
Travel expense (yuan/km × person)	0.27	0.3	0.5
Travel time (800 km, h)	3.4	8.4	2.5
Traffic volume(million/year)	160	80	16
Fatal accidental rate (person/billion km)	0.0018	1.92	0.014
Travel on-time rate (%)	98	75	75

Sources: Wanming Liu, "Study on Main Technical and Economic Issues of High-Speed Rail".

Our findings show that high-speed rail has great advantages in the comprehensive comparison of sustainable development for these three transportation tools. The development of the high-speed rail has an alternative effect to the use of cars and airplanes. It also reduces travel expense costs and saves travel time. From a comprehensive perspective, the high-speed rail has a significant role in promoting sustainable development in the transportation system in China.

4.3.2. Economic Growth

The investment of CHSR has stimulated investment in the national economy. Taking the earliest construction of the Beijing-Tianjin intercity high-speed rail as an example, the line mileage was about 120 km, with a total investment of 20 billion yuan; the line mileage of Beijing-Shanghai high-speed rail was 1318 km and the total investment is 220 billion yuan. Due to the global economic crisis in 2009, a large part of China's 4 trillion stimulus plan invested in infrastructure construction, of which the high-speed rail was a very important part.

The development of high-speed rail lines has a leading effect on the economic development of cities along the lines, which facilitates the contact between different economic regions and narrows the distance of time and space. Taking the Beijing-Shanghai high-speed rail as an example, we used the DID model to analyze the impact of it on the regional economic development.

We divided the process into two stages based on the implementation of the project, which named $t = 1$ and $t = 2$ respectively. Take the analysis of the impact of GDP along the Beijing-Shanghai high-speed rail as an example. The treated group is the GDP data of the high-speed rail cities along the Beijing-Shanghai high-speed rail, and the control group is the GDP data of the neighboring cities with no high-speed rail lines. The $t = 1$ is a stage that was before the construction of the high-speed rail line, and the $t = 2$ is a stage that was after the construction of the high-speed rail line.

The treated group is the area where the Beijing-Shanghai high-speed rail passes through. There are 19 cities in total. The 19 cities are Beijing, Langfang, Tianjin, Zhangzhou, Dezhou, Jinan, Tai'an, Jining, Zaozhuang, Xuzhou, Suzhou, Handan, Quzhou, Nanjing, Zhenjiang, Changzhou, Wuxi, Suzhou, and Shanghai. The control group is 12 cities with no high-speed rails before 2013, with a total of 12 cities. The specific data results are shown in Table 3.

Table 3. Results of DID Model.

Year	Treated Group (Thousand Yuan/Year)	Control Group	Treatment Effect
2009	49.4	28.7	20.7
2010	50.3	34.7	15.6
2011	57	39	18
2012	62.9	42.7	20.2
2013	86.1	45	41.1

Source: The author calculated this data from the "China City Statistical Yearbook."

Upon comparing the main economic indicators with the treated group and the control group, it can be determined that before the Beijing-Shanghai high-speed rail was opened, the absolute amount of GDP of the treated group cities was higher than that of the control group cities, with 20.7 in 2009

and 15.6 in 2010. In 2011, it was 18. In 2012, it was 20.2, and in 2013 it was 41.1. We can see that the average economic development rate of the treated group was faster than that of the control group. In addition, the gap between the two groups was gradually increasing (see Table 3). In other words, after the completion of the Beijing-Shanghai high-speed rail in 2011, the economic development rate of the area along the line has increased relatively faster than those adjacent areas with no high-speed rail lines.

4.3.3. Environmental Protection

The sustainability advantages of environmental functions are reflected through four aspects: noise, energy consumption, land occupation, and greenhouse gas emissions (see Table 4).

Table 4. Greenhouse Gases Emissions in 800 km for One Person.

Traffic Tool	High-Speed Rail	Car	Plane
Noise (50 m/dB)	64	70	100
Energy consumption (W × h/km × person)	184	279	523
Land occupancy	5.2	7.4	0.05
CO	4.6	510	225
NO _x	19.2	132	449
SO ₂	15.9	12	44
CH	0.44	42	17
CO ₂	25,000	71,000	139,000

Data sources: Wanming Liu, "Study on Main Technical and Economic Issues of High-speed Rail," Xuanyi Fu, "High Speed Rail and Resource Conservation," China Rail. Note: Noise is the average number of decibels 50 m away from the sound source. Energy consumption is based on the energy consumed by every person in every kilometer. Land occupancy is the permanent occupied land that is within 800 km. Greenhouse gases include emissions of several greenhouse gases within 800 km: CO, NO_x, SO₂, CH, and CO₂.

As we can see, the high-speed rail is more environmental friendly than the other two kinds of transportation tools. A large investment in the high-speed rail system in China would be a more sustainable development path.

4.3.4. Limitations

Of course, the development of the high-speed rail requires large capital and high technology. This determines that the developmental force of the high-speed rail could be only government or oligopolistic monopolies. In addition, except for a few lines that go through dense mega cities, high-speed rail projects are generally difficult to achieve profitability in the early stage of operation, and most of them may face premature debt crisis in the short-term.

4.4. Disruptive Innovation Pattern of CHSR

CHSR's disruptive innovation pattern is an innovation that has three implementation subjects including the government, enterprises, and research institutions. It relies on the interaction of three dominant factors including a policy guide, capital support, and human resources guarantee. It experienced three outbreaks that include a practical production outbreak, mass production outbreak and mainstreaming production outbreak. It ultimately accomplished the construction and operation of the world's leading high-speed rail system in a short time. The disruptive innovation stages could be concluded as:

1. Independent innovation
2. IDAR innovation
3. Integrated innovation
4. Innovation-led.

The disruptive innovation pattern of CHSR is depicted in Figure 6.

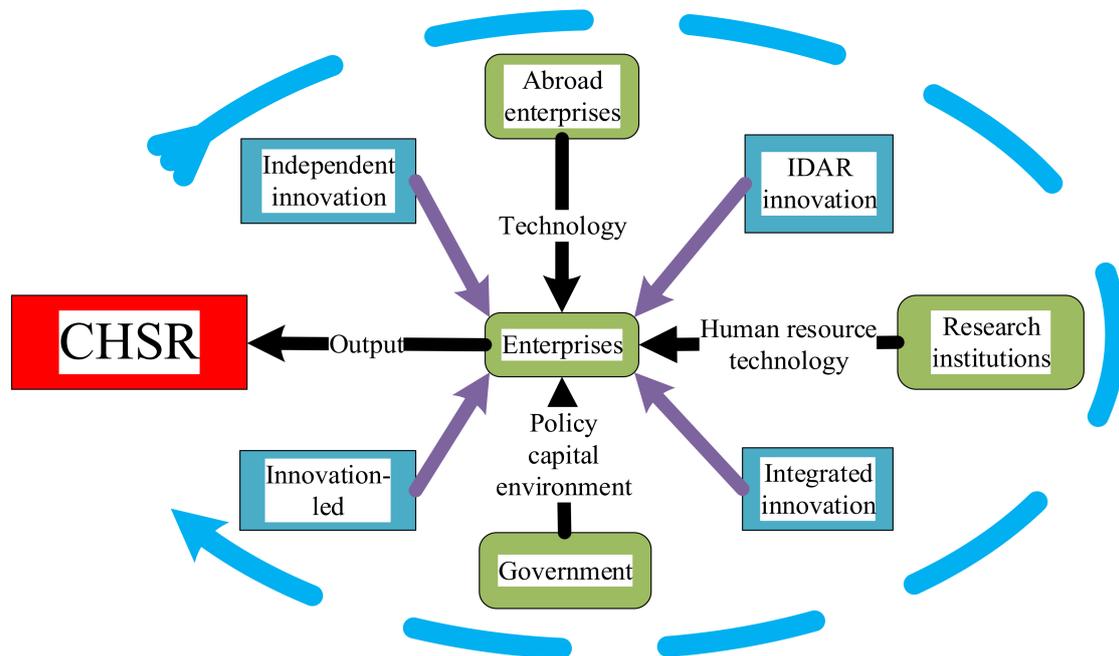


Figure 6. The disruptive innovation pattern of CHSR.

5. Discussion

5.1. Innovative Characteristics of CHSR's Pattern

Unlike traditional disruptive innovation, disruptive innovation driven by mega-project in China often require strong driving forces, often performed by the government or oligopolistic monopolies. In disruptive innovation activities of mega-projects, policy making is often the core element, human resource is the key to knowledge reservation, and capital plays the fundamental role in the development of technology. Moreover, the development of CHSR has also revolutionized the production process and operation of traditional railway. It has fostered a customer market that pursues efficient travel and changed the existing market rules and competition conditions.

5.2. Application Scope of CHSR's Pattern

The disruptive innovation pattern driven by mega-projects is generally applied to the public fields where the factors, such as capital and labor force, are not well market-developed; this means that the government's guidance is often required to help the development of the industry. In the long run, the disruptive technologies driven by mega-projects need market work more after their operation. The market-oriented reform of China's railways in recent years is based on such theoretical judgment.

5.3. Innovation Conditions of CHSR' Pattern

Independent innovation is the fundamental work. The government's scientific planning ensures the digestion and re-innovation of technologies from abroad. The vast market demand in China accelerates technology development and independent research. Oligopoly enterprises in the industry create the conditions for integrated innovation and competition. These macroeconomic environments are the beneficial bases for the tremendous achievements of CHSR.

6. Conclusions

Based on the connotation of disruptive innovation and connotation of mega-projects, this paper constructed a disruptive innovation connotation driven by mega-projects in China, which improved the connotation of sustainable management in this area. Based on this connotation, this paper analyzed the development pattern of the high-speed rail from its development process, operation mechanism, and influence in sustainability. We concluded that CHSR is a typical disruptive innovation, as well as a sustainable development driven by mega-projects, and it also constructed a disruptive innovation pattern for CHSR. The main conclusions are as follows.

CHSR's disruptive innovation pattern is an innovation that has three implementation subjects that include the government, enterprises, and research institutions. It relies on the interaction of three dominant factors including a policy guide, capital support, and human resources guarantee. It experienced three outbreaks that includes practical production outbreak, mass production outbreak, and mainstreaming production outbreak. It ultimately accomplished the construction and operation of the world's leading high-speed rail system in a short time. The disruptive innovation stages can be concluded as (1) independent innovation, (2) IDAR innovation, (3) integrated innovation, (4) innovation-led.

The rapid breakthrough and technological innovation of CHSR will have a profound impact on China's long-distance traffic in the long run. From this perspective, the development of CHSR is a disruptive development. Moreover, the contributions made by CHSR in energy conservation, emission reduction, and circular economy are obvious. From this perspective, the development of CHSR is yet another example of sustainable development. Thus, there is no conflict between sustainable development and disruptive development when it comes to CHSR project.

CHSR's development is a sustainable development in terms of transportation efficiency, economic growth, and environmental protection in China. For transportation efficiency, CHSR is more efficient than cars or airplanes. For economic growth, the GDP of cities along the high-speed rail lines accelerated after the operation of the high-speed rail. For environmental protection, CHSR reduces greenhouse gas emission and reduce the usage of lands, energy, and noise compared with other two main kinds of transportations. However, the developmental force of the high-speed rail can be only government or oligopolistic monopolies, which may be a restriction for its sustainable development unless more market mechanisms are imposed after its operation. In addition, except for a few lines that go through dense mega cities, it can be difficult to achieve profitability in the early stages of operation, but most of them may face premature debt crisis in the short-term.

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