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Continued Improvement or Disruptive Innovation: TOD Model Changes and Planning Strategies in Smart Cities

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Abstract: Transit-Oriented Development (TOD) model in smart cities not only demonstrates adherence to and continuity of traditional TOD planning principles but also showcases innovations in urban and planning methodology. Based on the degrees of continuation or challenge to the planning concepts and principles of traditional TOD model, this paper categorizes smart TOD model into two types: continued improvement and disruptive innovation. The paper compares smart TOD model and traditional TOD model from three aspects—the expansion and reduction of unit scale, the maintenance and transformation of urban form, and the continuation and innovation of functional mix. The findings reveal that both the expansion and reduction of unit scale represent the enhancement of the service capacity of smart TOD model over the traditional mode. The application of smart technology makes it possible to diversify urban forms. Furthermore, compared with traditional model, smart TOD model exhibits creative land use and architectural functions characterized by a future-oriented emphasis on non-traditional features, such as sharing and experiential elements. Based on the expanded connotations and development trends of smart TOD model, the paper finally proposes relevant planning strategies. It's highlighted that the future development of smart TOD model, leveraging smart technologies, should integrate the essence of community life circle, smart community, future community, and innovation district to achieve innovations in urban forms, functionality, and city space. **DOI:** 10.13813/j.cn11-5141/u.2024.0044-en

Keywords: smart cities; TOD; transportation hubs; unit scales; urban form; functional mix

Under the trend of smart city development, some cities have conducted conceptual planning research and practices with pioneering exploratory significance. Among these, a pivotal portion of smart city plans for transportation hubs and their surrounding areas have adopted the Transit-Oriented Development (TOD) model, emphasizing the principles and concepts of sustainable development. This approach aims to create compact urban forms, demonstrating new directions for integrating the TOD model with smart city planning.

The concept of TOD was first proposed by American urban designer and architect Peter Calthorpe. It centers around public transportation stations, creating mixed-use functional areas within a 5- to 10-minute walking distance, thereby forming efficient, compact, comfortable, and green urban districts and community hubs. Over time, through extensive application and dissemination, the TOD model has established a stable set of planning principles and concepts. For instance, it emphasizes a pedestrian-friendly radius, high-density development (Density), diverse land use (Diversity), and good design (Design). These "3D" principles have become the primary criteria for determining whether a plan aligns with the TOD model.

In the field of urban planning, related research has increasingly focused on exploring the intelligent development trends of transportation hubs (hereinafter referred to as "TOD hubs") and their surrounding areas under the TOD model. This includes discussion on the future direction of the TOD model [1-4], the spatial impacts brought by smart technologies such as big data and autonomous driving [5-8], the integration with intelligent public transportation technologies [9], the evolution of urban structures [10-12], and the promotion of transformative development in urban construction and operation methods [13], among other aspects. New concepts such as TOD 4.0 [2], TOD 5.0 [1], smart TOD model [3-5,12], TOD smart eco-city [13], and TOD future community [14] have also been proposed and discussed. This indicates that, during the smart city construction phase, the TOD model still holds stable value as a foundational framework for urban spatial layout.

In some smart city plannings, the TOD model exhibits significant differences from the traditional TOD model advocated by Peter Calthorpe in terms of unit scale, urban form, and functional mixing of land use and buildings, showcasing characteristics of creative attempts oriented toward the future. The thinking mirrored in these plannings and designs, particularly some of the innovations, not only represents certain trends in the development of the TOD model but also indicates critical reflections on the traditional TOD model. It is necessary to thoroughly analyze the inherent characteristics and implications of these innovations to serve as a reference for the planning and construction of TOD hubs and their surrounding areas in future cities.

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1 Changes in the TOD model in smart cities

In recent years, numerous conceptual planning practices for smart cities have been carried out both domestically and internationally. Among these, some planning practices have explicitly proposed the adoption of the TOD model, which can be summarized as the smart TOD model [3-5, 12]. For example, during the smart city planning and construction of Xiong'an New Area, principles such as public-oriented transportation, pedestrian dominance, mixed functionality, and compact development have been emphasized.

Internationally, many representative smart city plannings also frequently utilize public transportation networks as the developmental framework for urban construction, proposing intelligent and compact development around TOD hubs and their surrounding areas. Examples include Bitcoin City in El Salvador [15], The Orbit in Innisfil, Canada [16], Hammarby Lake City Eco-Town in Sweden [17], Telosa Smart City in the United States [18], the Line in Saudi Arabia [19], Hyundai Smart City Project in South Korea [20], and Xzero City in Kuwait [21]. These projects have all incorporated smart technologies, and their spatial layouts are closely related to the TOD model. The smart TOD model not only continues the planning concepts of the traditional TOD model but also challenges and criticizes it. Based on the extent to which they either continue or challenge the traditional TOD model's principles, the smart TOD model can be broadly categorized into two types: continued improvement and disruptive innovation.

1.1 Continued improvement

Continued improvement refers to the application of smart technologies while retaining the fundamental characteristics of the traditional TOD model, such as compact development, functional mix, and human-centered design, with partial modifications. Most of the aforementioned planning cases reflect the continuation of classic planning concepts and spatial layouts, such as the Garden City and Linear City, which use urban rail transit as the structural framework, while also introducing secondary innovations based on the traditional TOD model.

1) Continuation of layered and compact layout patterns

The overall structure of the traditional TOD model is preserved, with urban form and functional layouts largely consistent with the traditional model. For example, Bitcoin City in El Salvador (see Fig. 1a) draws inspiration from Ebenezer Howard's Garden City model, emphasizing low-carbon travel and smart transportation. It adopts a transportation structure combining light rail networks, bicycle systems, and pedestrian zones, while also prioritizing digital infrastructure development [15]. Similarly, The Orbit in Innisfil, Canada (see Fig. 1b), integrates fiber-optic networks and new rail transit systems. Centered around rail transit stations, it also references the Garden City model, using a concentric circular road network to arrange offices, residences, and other facilities. Building on the classic radial pattern of TOD, it proposes a layout combining circles and squares, creating a modern planning version that reflects European urban design characteristics [16].

2) Adoption of high-density, neighborhood-oriented patterns

This neighborhood design exhibits characteristics inspired by traditional cities, with less emphasis on layered patterns but featuring small-scale, dense road networks and human-centered neighborhood forms. The spatial layout demonstrates strong stability and adaptability. The application of smart technologies can be understood as a technical enhancement of traditional models. For instance, Hammarby Lake City Eco-Town in Sweden employs the TOD model, with continuously updated smart technologies. However, its planning and design adopt a high-density, neighborhood-oriented approach, adhering to the basic principles of form control and neighborhood shaping in traditional urban design [17] (see Fig. 1c).

a. Bitcoin City in El Salvador　　b. Orbit in Innisfil, Canada　　c. Hammarby Lake City Eco-Town in Sweden

Fig. 1 Continued improvement cases of TOD models in smart cities

Source: References [15-16].

1.2 Disruptive Innovation

Disruptive innovation refers to the application of smart technologies alongside radically innovative design approaches in spatial layout, resulting in significant differences or even opposite characteristics in unit scale, urban form, and functional mix compared to traditional TOD model. Some plans even reflect introspection and criticism on traditional TOD model.

1) Continuation of planning principles but disruption of urban form

The basic spatial layout of the traditional TOD model is overturned, creating entirely new spatial patterns. For example, The Line in Saudi Arabia (see Fig. 2a) is still based on urban rail transit and a modular TOD model, where all public facilities are within a 5-minute walk, and end-to-end travel is achievable within 20 minutes via high-speed metro. Spanning 170 km across valleys, mountains, deserts, and coastal areas, the city is developed on only 2% of the land area, leaving 95% for nature. The goal of this plan is to express the ambition of creating a "new wonder of the world" through a pure linear form, combining spatial design with smart technology to showcase both monumental and technical achievements. The compact urban form aims to protect the external ecological environment and natural spaces. The specific form and function of the plan feature a narrow and tall spatial layout, attempting to construct a 500-meter-high mixed-use building complex on a 200-meter-wide scale, which is entirely different from the traditional TOD model [19].

2) Changes in planning methods but continuation of urban form

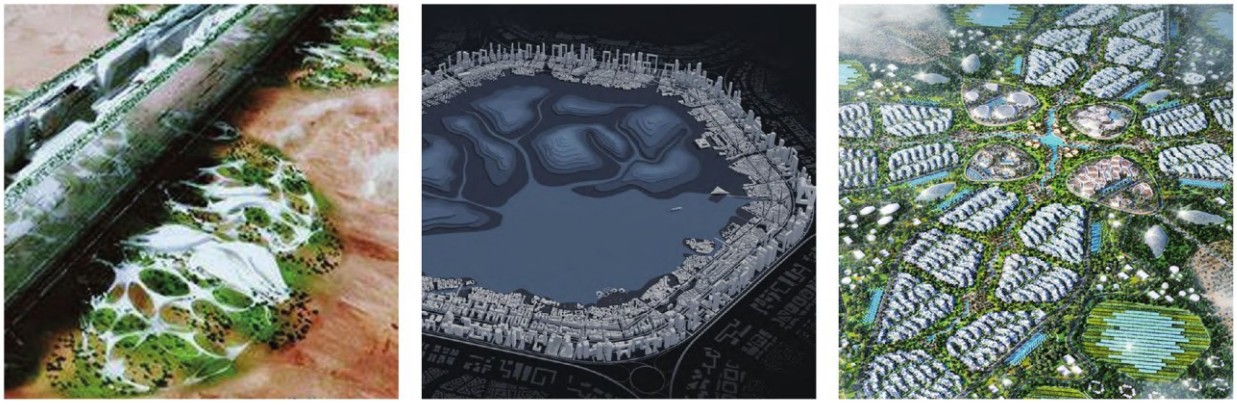
In some planning cases, transportation methods have evolved, challenging the principles of the traditional TOD model while retaining core values such as compact development, sustainability, and human-centered design. For example, the Hyundai Smart City Project in South Korea and Xzero City in Kuwait exhibit urban forms with high-intensity development at the center and lower intensity at the periphery, characteristic of the traditional TOD model. However, the central hub is not a traditional public transportation station but a transportation hub built around cars, drones, and autonomous vehicles [20-21]. Specifically, the Hyundai Smart City Project (see Fig. 2b) integrates autonomous vehicles and drone technology, splitting the compact development form of the traditional TOD model into two independent "semi-TOD" structures within a walkable scale [20]. Meanwhile, Xzero City (see Fig. 2c) retains the urban form of the traditional TOD model but introduces a butterfly-shaped design that directs vehicular roads directly into the core area through a narrowed "waist" where transfers are made to internal autonomous vehicle loops or pedestrian systems. This compact development does not rely on urban rail transit [21].

2 Comparison between smart TOD model and traditional TOD model

Referring to traditional model and its planning principles, the smart TOD model is compared with the traditional TOD model in terms of unit scale, urban form, and functional mixing.

2.1 Expansion and reduction of unit scale

The traditional TOD model emphasizes planning and construction centered around public transportation stations within a walkable scale. The walkable scale is a key feature of the traditional TOD model, typically defined as a 10-minute walk or a radius of 600 m. The primary trend in the smart TOD model is the expansion [3-4] or reduction of unit scales, driven by smart technology services, leading to a diversified development trend (see Fig. 3).



a. The Line in Saudi Arabia　　b. Hyundai Smart City Project in South Korea　　c. Xzero City in Kuwait

Fig. 2 Disruptive innovation cases of TOD models in smart cities

Source: References [19-21].

1) Unit scale consistent with the walkable scale of the traditional TOD model

Bitcoin City in El Salvador (see Fig. 4a) directly adopts the principle of a 600 m radius walkable scale [15]. The Orbit in Innisfil, Canada (see Fig. 4b), uses the classic two-tiered division of 400 m and 800 m radius from the traditional TOD model [16]. Meanwhile, the Hyundai Smart City Project in South Korea establishes three types of interconnected neighborhoods between main roads and natural environments, with neighborhood side lengths of 200 m and an overall width of 600 m, equivalent to a 9-minute walk [20].

2) Expansion of the radius based on the walkable scale of the traditional TOD model

The Kashiwa-no-ha Smart City in Japan, particularly around Kashiwa-no-ha Campus Station (see Fig. 4c), proposes expanding the radius of the traditional TOD model to 2 km by integrating autonomous bus connection. This feature is also reflected in projects such as Ōmiya Station in Saitama City and Shibuya Station in Tokyo, where the radius is expanded to 2.0–2.5 km [4, 12, 22].

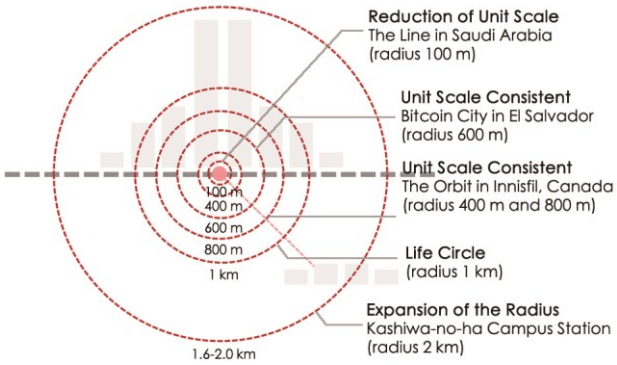
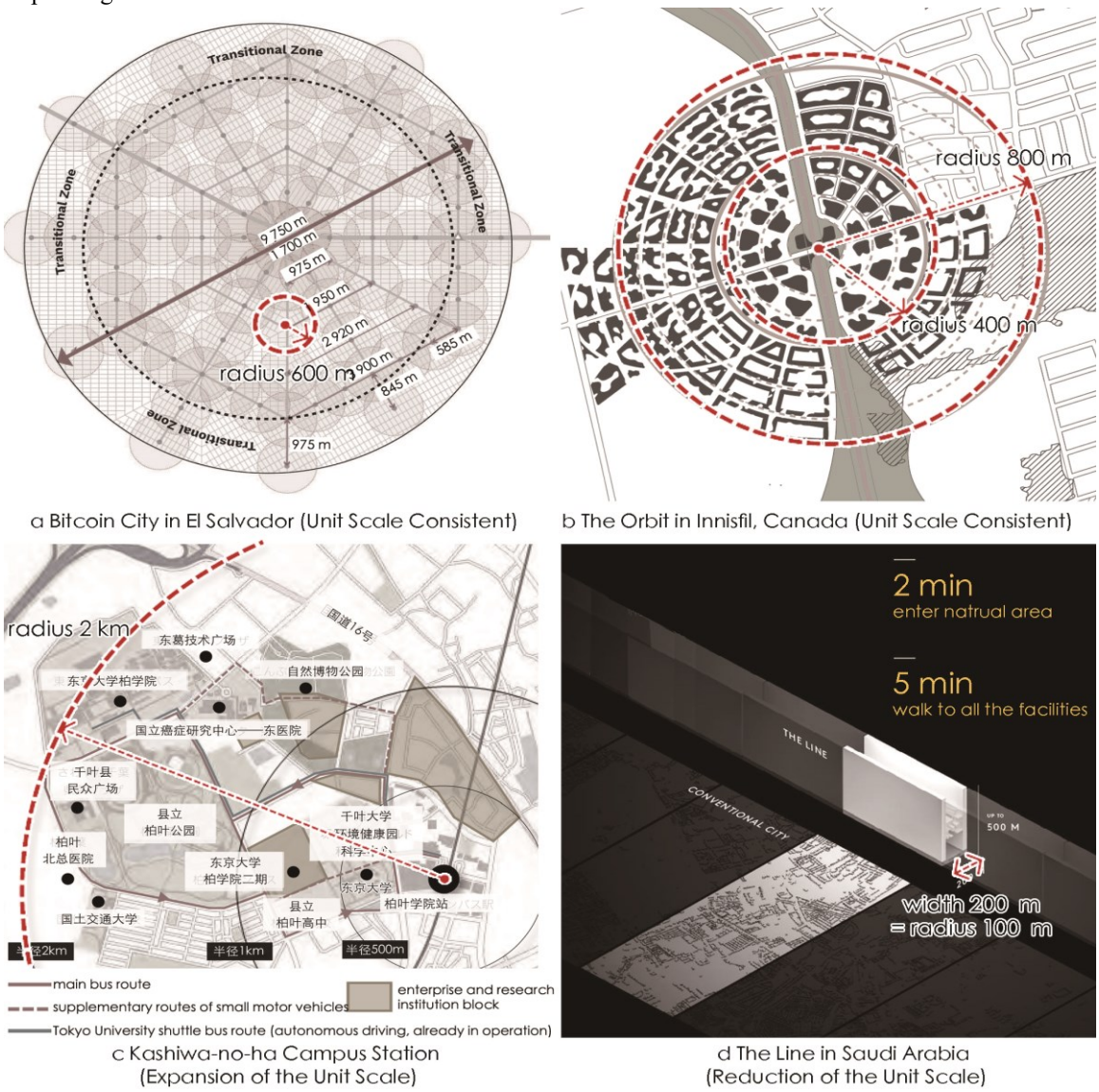


Fig. 3 Expansion and reduction of unit scales



a Bitcoin City in El Salvador (Unit Scale Consistent)

b The Orbit in Innisfil, Canada (Unit Scale Consistent)

c Kashiwa-no-ha Campus Station (Expansion of the Unit Scale)

d The Line in Saudi Arabia (Reduction of the Unit Scale)

Fig. 4 Planning cases of expansion and reduction of unit scales

Source: Reference [12, 15-16, 19].

3) Reduction of the radius based on the walkable scale of the traditional TOD model

In The Line in Saudi Arabia, the distance between the two high walls is 200 m, equivalent to a radius of only 100 m. Travel time is primarily distributed along the linear axis of the city and the vertical travel dimension with a height of 500 m [19] (see Fig. 4d).

Overall, whether the unit scale is expanded or reduced, both represent an enhancement of the service capability of the smart TOD model compared to the traditional TOD model. The former signifies spatial expansion on a horizontal level, while the latter, based on horizontal contraction, pursues vertical expansion.

2.2 Preservation and transformation of urban form

An important layout feature of the traditional TOD model is the variation in building height and development intensity, with higher density at the center and lower density at the periphery, promoting compact development. Some smart city plans continue to maintain this high-intensity development within a walkable scale, while others take a different approach, shaping distinct urban forms while adhering to the principles of the traditional TOD model (see Fig. 5).

1) Preservation of urban form

In Bitcoin City in El Salvador, the design of key urban nodes exhibits spatial layout characteristics of New Urbanism, with high-intensity compact development centered around stations [15] (see Fig. 6a). The urban forms of The Orbit in Innisfil, Canada, and Xzero City in Kuwait display the typical layered layout of high density at the center and lower density at the periphery [16, 21]. Similarly, Kashiwa-no-ha Campus Station and its surrounding areas in Japan, as well as Telosa Smart City in the United States, adopt compact development centered around stations [12,18] (see Fig. 6b). The spatial layout of Hammarby Lake City Eco-Town in Sweden also adheres to the principles of compact layered development. However, due to its overall urban form featuring low-rise, multi-layered neighborhood patterns, the differences between layers are less pronounced compared to other planning cases [17].

2) Transformation of urban form

The Line in Saudi Arabia is particularly unique. While the early planning proposal envisioned a layout of 5-minute walk clusters around rail transit stations [23], the later construction plan proposes a more extreme approach. The city is 200 m wide, 500 m high, and 170 km long, with a spatial layout that does not extend to a radius of 600 m or more. Instead, it creates an extreme "narrow and tall" form [19] (see Fig. 6c). In terms of Hyundai Smart City Project in South Korea, although it forms a gradually stacked form based on the functional characteristics of different blocks, it adopts a hexagonal layout for its basic units, resulting in a "semi-TOD" urban form with unilateral clustering [20] (see Fig. 6d).

Overall, the smart TOD model exhibits features of compact development in urban form, and the application of smart technologies makes it possible to achieve greater diversity in urban morphology.

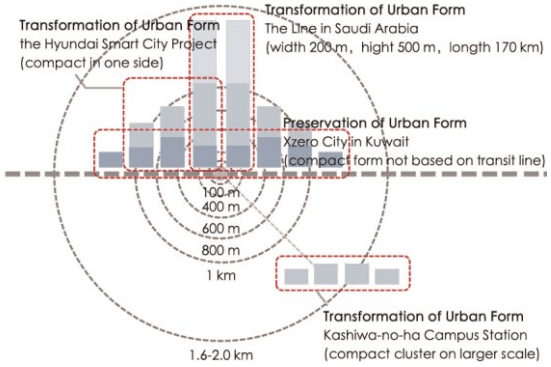


Fig. 5 Preservation and transformation of urban forms

2.3 Continuation and innovation of functional mix

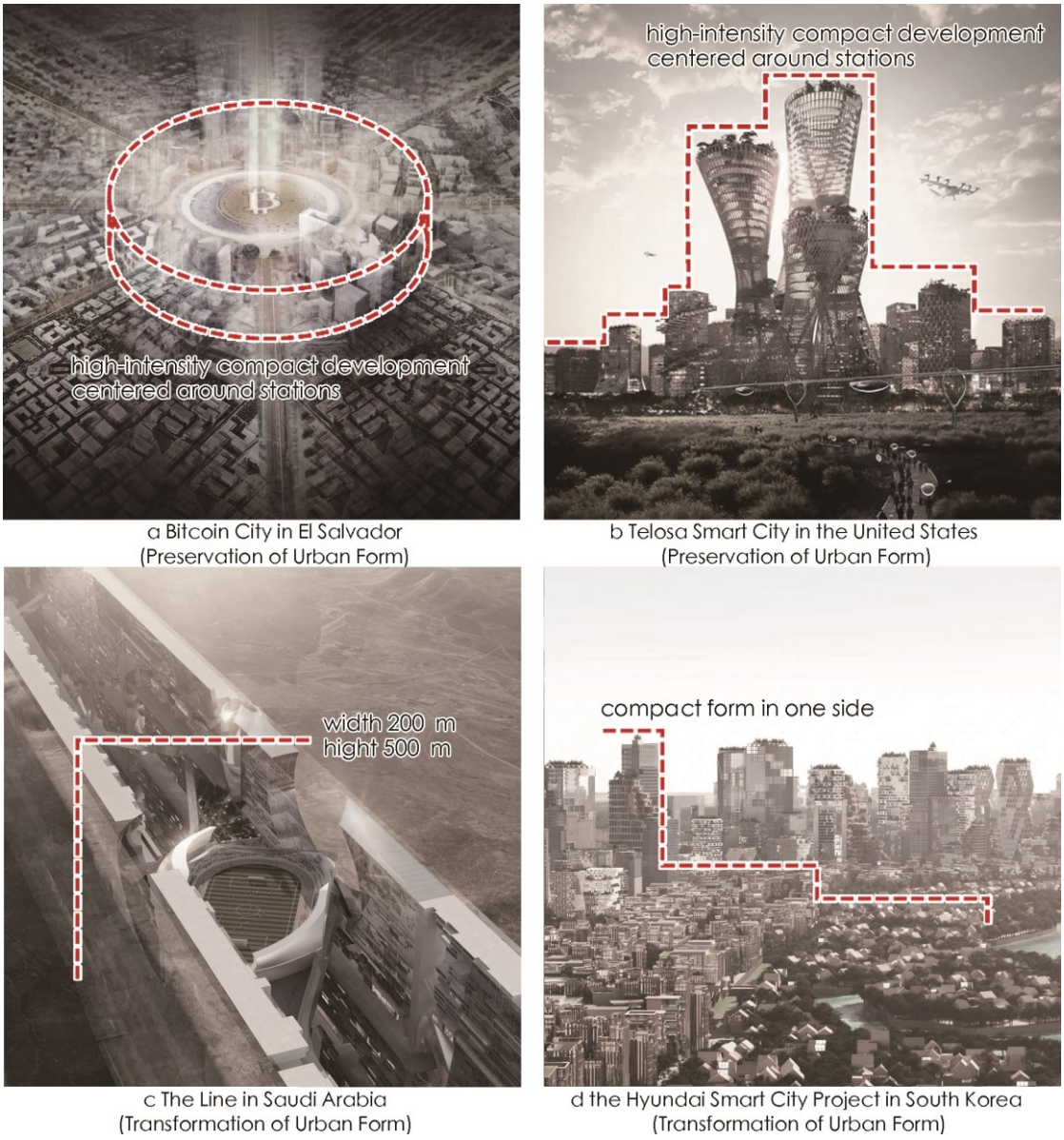
The traditional TOD model emphasizes the mixing of functions in and around TOD hubs, including spatial mixing (e.g., complexes combining office, residential, and commercial functions), job-housing balance, and temporal mixing (e.g., extending the vibrancy of public activities to 18 hours or more daily through functional mixing). In the smart TOD model, functional mix is more closely related to future-oriented innovations [3-4]. Some plans innovate in the functional mixing of urban rail transit station complexes, while others adopt more extreme methods, strengthening horizontal connections in the upper parts of super high-rise buildings to create more tightly integrated vertical functional mixing and innovation (see Fig. 7).

1) Continuation of functional mix

Bitcoin City in El Salvador continues the principle of mixed land use in a neighborhood-oriented manner, arranging public facilities and mixed-use buildings along the city center and main streets [15] (see Fig. 8a). The Hyundai Smart City Project in South Korea concentrates functional mix in the podium sections of high-rise buildings and mid-to-low-rise structures [20] (see Fig. 8b). Both Telosa Smart City in the United States and Kashiwa-no-ha Smart City in Japan propose urban designs with functional mix at the neighborhood level [12,18].

2) Innovation in functional mix

In the Knowledge Capital project within the Osaka Station Front Complex in Japan, the core large-volume space is designed as an innovative, future-oriented experiential and shared space, including co-working offices, knowledge salons, corporate future life pavilions, industrial labs, and



a Bitcoin City in El Salvador
(Preservation of Urban Form)

b Telosa Smart City in the United States
(Preservation of Urban Form)

c The Line in Saudi Arabia
(Transformation of Urban Form)

d the Hyundai Smart City Project in South Korea
(Transformation of Urban Form)

Fig. 6 Planning cases of preservation and transformation of urban forms

Source: References [15, 18-20].

cultural facilities such as theaters and exhibition halls [24] (see Fig. 8c). The Line in Saudi Arabia proposes functional mixing at different heights within its 500-meter-high street walls, even planning to incorporate reception, education, healthcare, and leisure functions in the upper sections of the buildings. However, whether these ambitious goals can be perfectly achieved in practice remains to be observed [19](see Fig. 8d).

Overall, the continuation and innovation of functional mixing are key features of the smart TOD model. However, compared to the traditional TOD model, the mixing and innovation of land use and building functions in the smart TOD model are more future-oriented, emphasizing non-traditional shared and experiential characteristics.

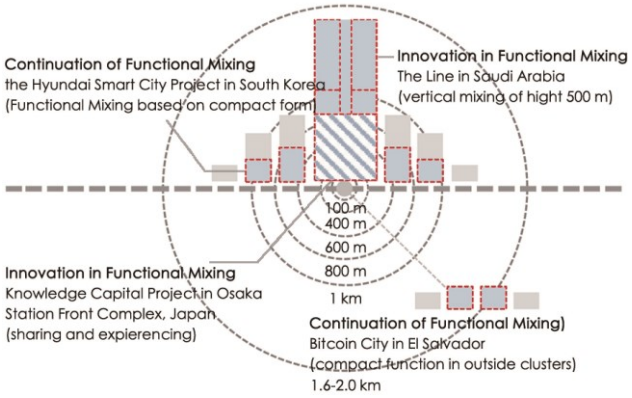


Fig. 7 Continuation and innovation in functional mix

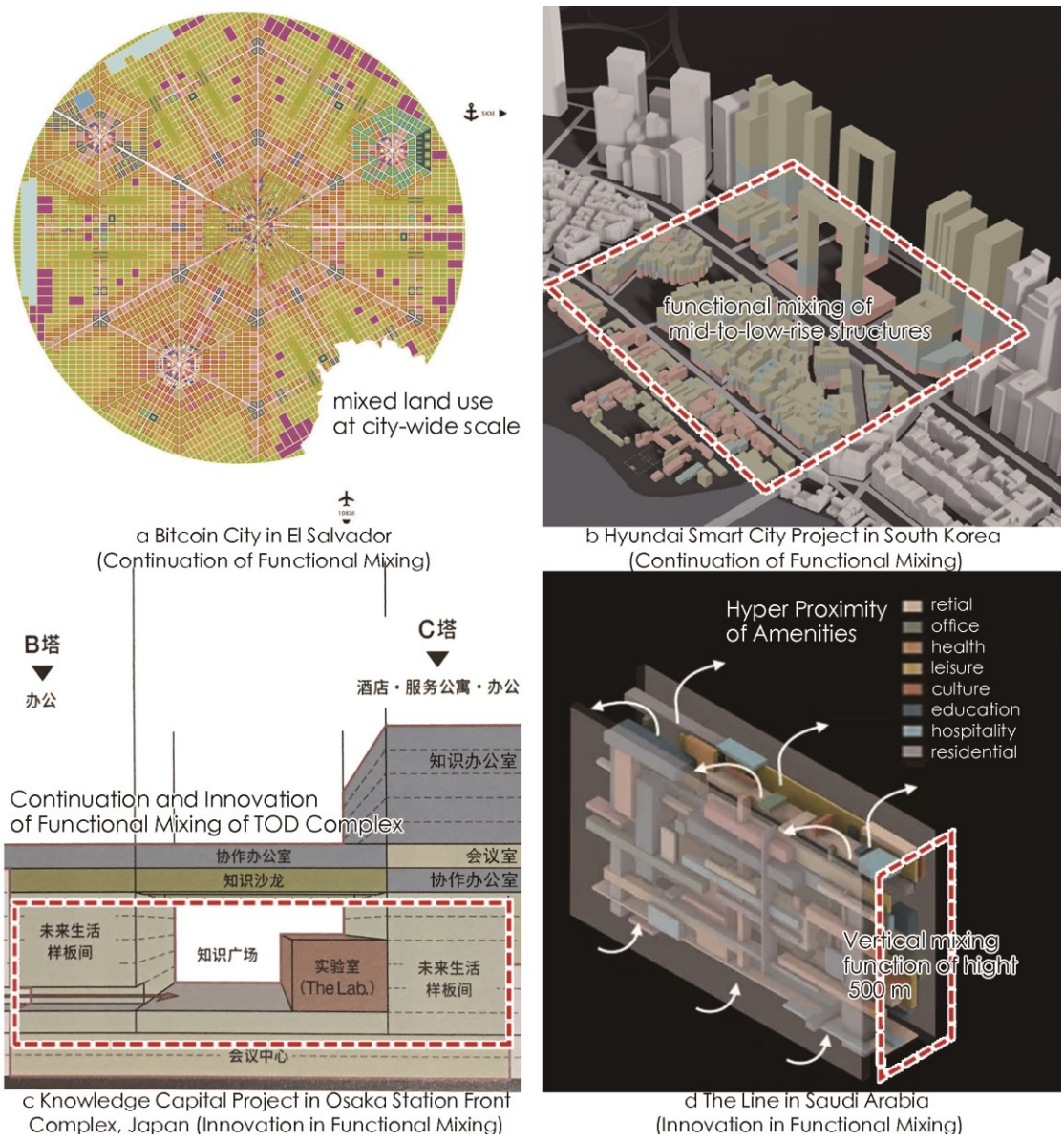


Fig. 8 Planning cases of continuation and innovation in functional mix

Source: References [15, 19-20, 24].

3 Connotation and development trends of the smart TOD model

3.1 Expansion of TOD connotation

Does the TOD model necessarily require public transportation to guide it [25]? Are the planning principles of the TOD model stable and effective for the future development of cities [26]? Will the TOD model be continued or dissolved [3]? Does the TOD model represent future trends and visions [27]? These are all topics worthy of examining repeatedly.

The TOD model is an urban development model guided by public transportation, but it is not limited to rail transit as the sole transportation system. It includes various public transportation modes such as buses and rapid transit, with compact and sustainable development being the core connotation of the TOD model. The development of smart cities provides new perspectives on the future trends of the TOD model. Emerging transportation methods in smart cities, such as autonomous vehicles and drones with shared characteristics, have expanded the connotation of the TOD model. Autonomous transportation exhibits the features of both public and shared transportation. Based on this understanding, the “T” in TOD has become more diverse in form, but the essence of public transportation remains unchanged.

New transportation technologies have inspired radical visions for urban forms [28]. Against the backdrop of smart technology development, some smart city plans objectively

challenge the traditional TOD model. For example, the Hyundai Smart City Project in South Korea and Xzero City in Kuwait both provide new "public transportation" methods through autonomous vehicles and drones without emphasizing rail transit, creating a hexagonal TOD corridor similar to Curitiba's public transportation corridor. Meanwhile, The Line in Saudi Arabia, while utilizing high-speed metro, significantly alters unit scale, urban form, and land use functions, resulting in a spatial layout entirely different from the traditional TOD model. A comparison between the smart TOD model and the traditional TOD model is shown in Fig. 9.

3.2 Multi-mode integration

The advancement of smart technologies will drive innovations in lifestyle, work methods, and industries, with these aspects being closely interrelated. The development trend of the smart TOD model is not merely a singular integration with smart technologies but also involves convergence with new urban planning models such as community life circle, smart community, future community, and innovation district. These models influence and learn from one another. The community life circle, future community, and innovation district models emphasize the layout of facilities centered around public transportation stations and the application of smart technologies. The community life circle, smart community, and future community models also focus on serving innovative populations, while the innovation district model prioritizes the creation of community living units and the application of smart technologies. The integration of these models not only brings about a convergence of values toward future ideal urban concepts but also leads to the complexity of the model structures of ideal urban units, namely the compounding of TOD structures.

The smart TOD model generally incorporates the integration features of the aforementioned models. For example, Telosa Smart City in the United States adopts the 15-minute city concept for its overall spatial layout. The Line in Saudi Arabia applies the 5-minute walking principle at the ground level, exhibiting characteristics of the TOD model, smart community model, and community life circle model. The Osaka Station Front Complex in Japan, developed around Osaka Station, embodies the TOD model. Simultaneously, the Knowledge Capital project within the complex is both a smart city initiative and an innovation district project, featuring shared workspaces, technology experiences, and other innovative functions. This demonstrates the integration of the TOD model, smart community model, and innovation district model [24]. The Orbit in Innisfil, Canada, combines the 15-minute life circle and complete community concepts to design an ideal urban structure [16,18-19].

As shown in Fig. 10, the smart TOD model with integrated features exhibits a different structure from the traditional TOD model. It promotes the non-central units (within the red circle) and central units, around urban rail transit stations, within a radius of 1.6–2.0 km or larger scales, to have more comparable service capabilities and travel conditions. With the help of autonomous driving technology, drone technology, and online shopping platforms, the locational differences between transportation hubs and nearby stations are leveled. Within a 2 km radius of the smart TOD model, differences in travel time are reduced, and within a 3 km

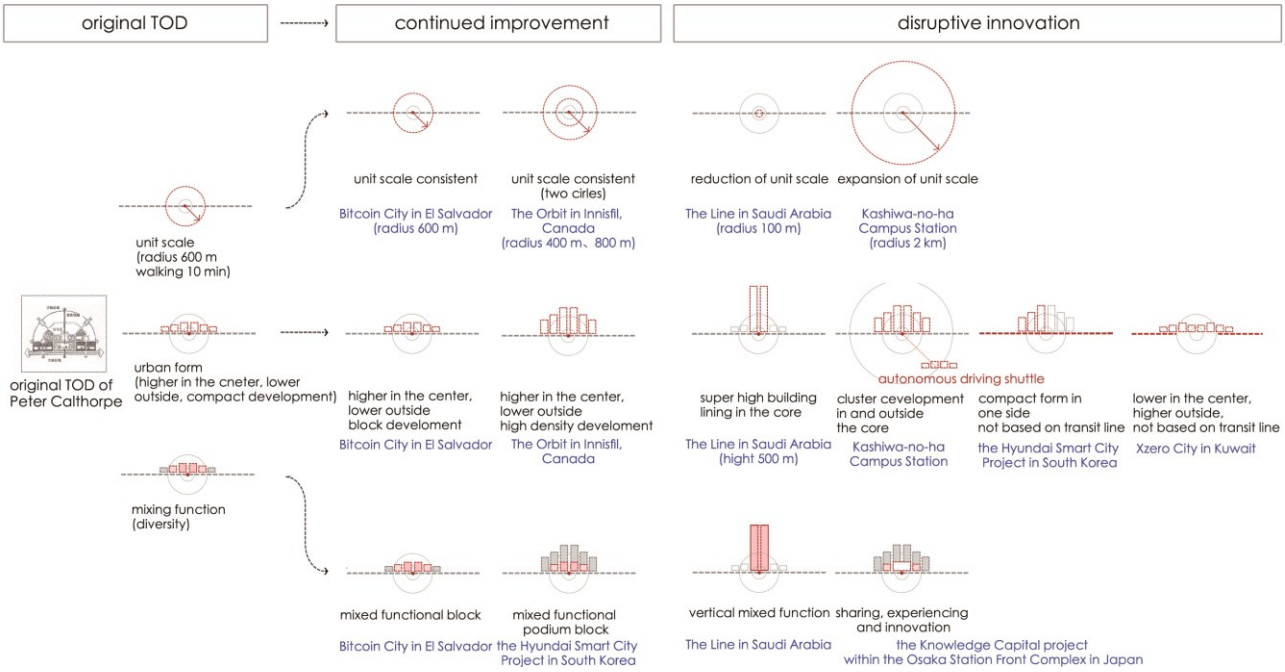


Fig. 9 Comparison of smart TOD and traditional TOD models

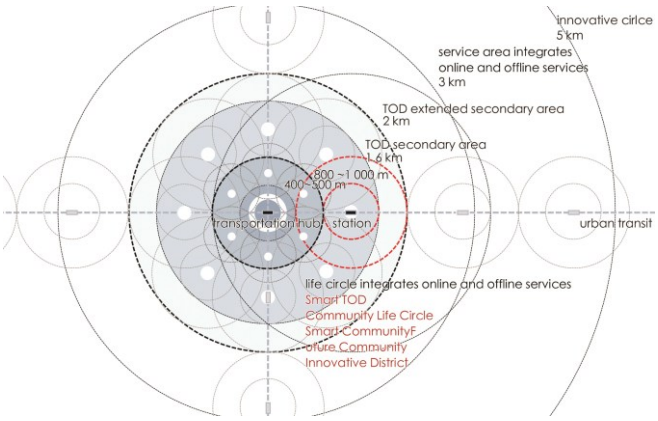


Fig. 10 Integrated smart TOD models

Source: Reference [29].

radius, differences in service access time are minimized, leading to more homogeneous locational value. Additionally, by leveraging public transportation services, the configuration of innovative functions can be expanded to a scale of 5 km [29].

4 Planning strategies for the smart TOD model

4.1 Exploring model innovation by balancing basic connotation and integration needs

The TOD model represents a revolutionary improvement over modernist urban planning [1], with rich connotations [30]. Regardless of the transportation mode, as long as it is guided by public transportation development, featuring low-carbon, sustainable, compact urban form, and human-centered public spaces, all can be countered as TOD model. Building on this foundation, innovative explorations should be conducted to meet the needs for developing future smart cities.

1) Combine the TOD model with community life circle, smart community, future community, and innovation district [29]. Align with the trend of online and offline community integration to merge urban spatial units with shared value into a new smart TOD model.

2) Summarize the smart TOD model to different spatial conditions based on China's current needs for smart city development, urban renewal, and city-industry integration.

3) Based on the planning case experience, emphasize factors such as scale, functional innovation, morphological evolution, and spatial organization [3,4,12] to develop differentiated indicators and guidelines.

4.2 Innovating urban form and spatial layout based on smart technologies

Smart technologies and new lifestyles are driving changes in future urban spaces [11], with transportation innovations being a key influencing factor [6]. In smart city construction, the integration of various flows, fields, and networks will create new synergies [31], and urban rail transit stations and their surrounding areas will serve as ideal spatial nodes for this integration. With advancements in drones, autonomous vehicles, and urban rail transit technologies, the TOD model is expected to evolve further [1,3,8]. Whether through evolutionary improvement or disruptive innovation, the development of the traditional TOD model should continue while maintaining its core planning principles. Future smart city development should leverage smart technologies to innovate urban forms, functions, and spaces.

1) Introduce innovative functions such as shared workspace and immersive technology experiences in and around TOD hubs to enhance their intrinsic value and attractiveness.

2) Beyond maintaining the traditional compact, layered layout of the TOD model, explore new possibilities for morphological evolution by integrating smart technologies like drones, autonomous vehicles, and intelligent public service facilities.

3) Address new demands and conditions for smart development in TOD hubs and their surrounding areas by innovating spatial scenarios in smart cities, such as autonomous vehicle shuttles, drone delivery services, and designs that promote online-offline integration.

4.3 Innovating comprehensive collaborative planning and operational mechanisms

The innovative exploration of the smart TOD model involves not only spatial imagination but also addressing multidimensional development needs and complex contextual conditions. For example, Bitcoin City in El Salvador embodies the country's aspiration to get rid of the control of the US dollar and achieve economic independence [15]. As Japan's first smart city prototype, Kashiwa-no-ha Smart City aims to create a future-oriented model for integrated industry-academia-research development [12]. These projects require innovative mechanisms for smart city operations to reconcile diverse demands [32] and promote multi-stakeholder participation [4]. Innovations in planning and operational mechanisms for the smart TOD model are reflected in the following aspects:

1) Emphasize the role of smart technologies in advancing urban construction and social life. Integrate technological progress, needs for urban economic development, and trends of evolving work and lifestyle to holistically address the comprehensive demands of smart development in TOD hubs and their surrounding areas, creating targeted spatial solutions and mechanism designs.

2) From the perspective of urban operation and management, coordinate and integrate the entire chain of planning, investment, development, construction, and operational management for future-oriented TOD hubs and their surrounding areas, exploring mechanisms for sustainable development.

5 Conclusion

The smart TOD model encompasses both evolutionary improvements and disruptive innovations to the traditional TOD model, reflecting both the preservation of traditional TOD planning principles and the innovation of planning methods. For example, The Line in Saudi Arabia, regardless of its future construction outcomes, serves as a mirror for reflecting on the traditional TOD model and a valuable reference for TOD innovation through the strengths and issues highlighted in its planning and design. Although these bold planning concepts and designs may not be fully realized, they will, like the Garden City, an ideal urban planning concept that was never fully built but had a profound impact on urban development, serve as important milestones on the path to developing future smart TOD models, providing guidance and inspiration for future endeavors.

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