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COMMENTS

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Underground logistics systems: Development overview and new prospects in China

1 Introduction

Underground logistics systems (ULSs) are a set of self-contained, multimodal, and intelligent physical distribution concepts that enable the automated movement of goods via tunnels and underground pipelines installed within and between cities (Visser, 2018). ULSs are also recognized as the fifth type of logistics and generic supply system after seaways, airlines, roads, and railways (Qian and Guo, 2007). ULS strategies aim to transform the traditional traffic organization into a "people aboveground, freight underground" pattern and foster the development of modern transportation and logistics industries to become fair, smart, and sustainable (Qian, 2016). The logistics modal shift from roads to underground can generate broad external benefits, such as decreased traffic congestion, improved traffic safety and resilience, land saving, and carbon footprint reduction (Chen et al., 2017). Since the 1970s, governments and institutions around the world have experimented on ULSs and proposed diverse system solutions for various application scenarios (The ASCE Task Committee on Freight Pipelines of the Pipeline Division, 1998; Egbunike and Potter, 2011). Unfortunately, most early efforts failed to transform into political impetus owing to inappropriate strategic positioning, lack of awareness, or insufficient social demand.

It is noteworthy that the most recent ULS initiatives received government support and are about to be built or completed (Beijing Municipal Commission of Planning and Natural Resources, 2018; Swiss Federal Council, 2020; Management Committee of Xiong'an New Area of China, 2021). A salient trend is the strong alignment of such projects with national strategies. In China, ULSs were incorporated into the state's 14th Five-year Plan for Transportation Science & Technology Innovation (China State Council, 2019; Ministry of Transport of China, 2022) and modern logistics system development (National Development and Reform Commission, 2022), thereby endowing ULS programs with new connotations regarding smart urbanization, transport integration, carbon neutrality, underground space exploitation, transit-oriented development, emergency capacity upgrading, and so on (Guo et al., 2021). Through the top-down lens, ULS adoption or abandonment is no longer dominated unilaterally by finance or marketing factors, but rather, crucial to consider new values and the significance of introducing ULSs to a country and the public.

A literature survey showed that ULS research is in its infancy, and many key system engineering issues have yet to be solved or perceived. Compared with hardware technologies, ULS engineering management is a brand-new research field and consists of multidisciplinary knowledge. A dedicated body of knowledge is necessary to lay the theoretical and methodological foundations for the forthcoming practice and project decision making.

This work gives a brief review of the ULS development history and status quo within a global range and describes the main visions for ULS development in China. Aligning with the management science and engineering domain, this work emphasizes some academic issues for future ULS research.

2 ULS initiatives and recent progress

Underground freight transport concepts originated from

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the emergence of pneumatic capsule pipeline (PCP) technologies at the beginning of the 19th century, when small-diameter (5–20 cm) PCP segments were installed in European cities to transport letters and telegrams beneath congested streets. In 1914, Chicago built the world's first multipurpose underground physical distribution network across downtown districts. A similar infrastructure is the London Mail Rail system built in 1927. The concept of modern ULSs first appeared in a research project sponsored by the Department of Transportation of the United States called "Transport of Solid Commodities via Freight Pipeline", which investigated the feasibility of introducing high-speed automated tube freight technologies (underground) into long-haul logistics (Zandi et al., 1976). Based on the literature, Table 1 summarizes the major ULS initiatives proposed since the 1970s, including ready-built systems, abandoned proposals and concepts, suspended plans, and projects under discussion or development. Generally, such plans are under three main objectives: i) building tunnel corridors between cities to transport batch goods, ii) building freight tunnels or pipeline networks within cities for urban underground delivery, and iii) building point-to-point underground connections to support fast cargo transfer within local ranges.

A long-term debate on ULSs is whether such systems are provided by the private sector or public sector. ULS proposals in Europe and in the United States are motivated by the needs of markets or industries for advanced pipeline transportation technologies; thus, a major objective is to solve the operational bottlenecks of companies' supply chains to deliver improved logistics services to customers. For example, the Cargo Sous Terrain (CST) project, which received Swiss legislative support, was initiated by consortia and industrial partners. Virgin Hyperloop is developing an ultra-high-speed vacuum freight tube technology, and its first step is to seek collaboration with state-operated businesses. In this context, the commercial value and economic viability of ULSs are highlighted. Other plans with governmental involvement aimed to meet specific logistics needs, such as port operations (Alameda Corridor project) and business between shippers and local carriers (Ondergronds Logistiek Systeem Schiphol' (OLS-ASH) project). Such proposals may function as an alternative to the road transport process but are not a new holistic logistics solution, as the logistics organizational mode is unchanged.

Asian countries view ULSs as a government-led initiative to alleviate "megacity diseases" and promote sustainable urban development. The stratified city concept incorporating urban ULSs was first described by Japanese architect Toshio Ojima in 1986. The Tokyo L-net, which is an official follow-up research project, investigated the feasibility and social benefits of developing a citywide underground infrastructure network to carry out urban freight transport. China and Singapore are the main practitioners in urban ULSs after 2010. The 2030 Singapore Land Use Plan mentioned an Underground Goods Mover System (UGMS) connecting warehousing facilities in underground rock caverns with residential units (Zhou and Zhao, 2016). In recent years, China disclosed several

Table 1 Summary of global ULS initiatives (1970s–present)

Purpose	Name of plan	Country	Active period	Status	Main source of goods	Length
Intercity transport	Freight Tube	United States	1976–1998	Rejected	Supply chains	700 km
	Freight Shuttle	United States	1999–present	Planning/Prototyping	Port containers	434 km
	PCP Container	United States	2000–2008	Rejected	Port containers	320 km
	Pipe§net	Italy	2008–present	Planning/Prototyping	Supply chains	200 km
	Virgin Hyperloop	Saudi Arabia	2015–present	Preparing for building	Retail & Expressage	951 km
	CST	Switzerland	2016–present	Preparing for building	Supply chains	450 km
	Magway	United Kingdom	2018–present	Planning/Prototyping	Retail & Expressage	Unknown
Urban delivery	Tokyo L-net	Japan	1990–2000	Rejected	Retail & Expressage	300 km
	CargoCap	Germany	1996–2008	Suspended	Supply chains	80 km
	UGMS	Singapore	2013–present	Planning/Prototyping	Retail & Expressage	Unknown
	Xiong'an Smart Utility	China	2017–present	Under construction	Retail & Expressage	15 km
	Beijing Municipal Administrative Center	China	2018–present	Planning/Prototyping	Expressage	38 km
	CargoSpeed	United Arab Emirates	2019–present	Planning/Prototyping	Retail & Expressage	Unknown
Local transfer	OLS-ASH	Netherlands	1994–2005	Rejected	Airport	25 km
	Envac	Global	1990s–present	Applied	Municipal waste	< 10 km
	Alameda Corridor	United States	2002–present	Applied	Port containers	32 km
	Underground Container Mover	Belgium	2004–2006	Rejected	Port containers	20 km
	Underground Container Transportation System	China	2010–present	Planning/Prototyping	Port containers	30 km

urban ULS programs in the controlled detailed plans of new cities. In the Xiong'an New Area, underground freight corridors were integrated into a newly built utility tunnel system, where external goods would be distributed directly to designated blocks and buildings through underground networks.

As a pioneering project, the introduction of ULSs is associated with various complex factors. Different supply–demand relationships and upper policies among societies may lead to divergent attitudes toward ULSs. Strategies under public provision and private provision face different preconditions, challenges, and opportunities. Collaborations among governments, industries, and research communities may be strengthened after ULSs advance to a substantial development stage. New breakthroughs in ULS practice are expected with the increasing fusion of policy/strategy push and market/technology pull.

3 Prospects of ULS development in China

Figure 1 depicts three strategic visions and four key tasks for ULS development in China.

3.1 Towards smart urbanization

Chinese modernization faces challenges from the large-scale migration of rural populations to big cities. The country's new-type urbanization strategies focus on optimizing urban spatial patterns and developing modern metropolitan areas embedded with steric transportation infrastructure networks and smart logistics systems. To achieve such visions, solving the current pain points of the road-dominated logistics mode is urgent. The negative influences include i) land resource damage from the relocation of logistics facilities in response to urban renewal or expansion, ii) decline in economic circulation efficiency owing to strict traffic restrictions on truck access to cities, iii) road congestion caused by the illegal behavior of use of private cars for logistics businesses, iv) traffic safety hazards from the employment of massive couriers and crowdsourcing riders in last-mile delivery, and v) poor supply capacity during extreme weather conditions or pandemic outbreaks. ULSs can offer a package of solutions to the above problems by shifting freight traffic underground. In China's smart city pilot planning, ULSs are considered to be a preferential option to enhance the city's potential and identity.

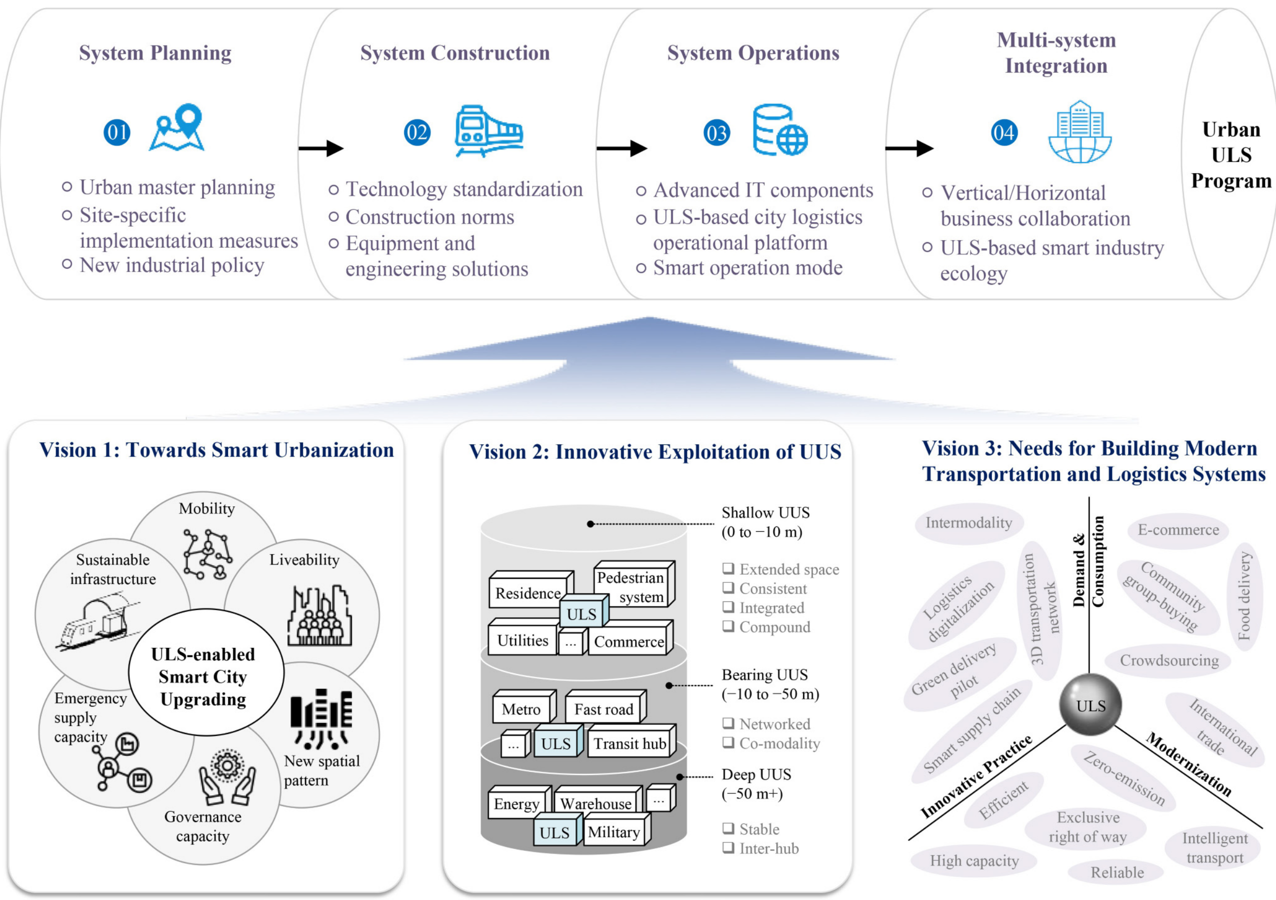

Fig. 1 China ULS strategies: Visions and tasks.

3.2 Innovative exploitation of underground space

The total exploitation scale of urban underground space (UUS) in China has exceeded one billion square meters, thereby ranking first in the world (Yang et al., 2021). China's innovative UUS exploitation practice is increasing rapidly but remains in the preliminary stage, with most mid-deep underground space resources remaining untapped. The hierarchical deployment of ULS facilities (e.g., underground container railways and neighborhood-level smart freight pipelines) well-matches the stratified UUS utilization strategies in China. Thus, a long-term vision is to develop hyperconnected underground infrastructure networks comprising ULSs, public transit, pedestrian systems, commercial zones, and so on. Meanwhile, ULSs can enrich UUS function by enabling the co-mobility of people and goods.

3.3 Needs for building modern transportation and logistics systems

China established the largest and most prosperous city logistics markets in the world, with the domestic express business volume reaching 108 billion pieces in 2021 (30% higher than that in 2020) and a 15% growth rate in the national logistics revenue. The state's 14th Five-year Plan called for building an efficient city logistics service system and multimodal transport infrastructure networks to meet the challenges of surging goods movement demand. ULS programs can not only make up for the shortcomings of traditional city logistics in terms of economy of scale, capacity, efficiency, and reliability but also fit the development orientation of China's modern transportation and logistics systems (e.g., just-in-time service, smart warehousing, zero-emissions traffic, and sustainable delivery). In addition, China's related visions and industrial policies, such as building global freight rapid transit circulation systems and promoting urban green delivery pilots, metropolitan intermodality, and logistics digitization, are conducive to the promotion of ULS strategies.

3.4 Outlooks for implementing ULS strategies

Planning. The priority of ULS planning is to clarify the overall system development guidelines and goals in the urban master plan. Specifically, recalibrating current protocols with respect to the avoidance and preservation of UUS to minimize conflicts between the planning of ULSs and other underground systems is crucial. Other site-specific methods for developing ULSs in urban China (e.g., co-building of ULSs with metro or underground utilities) must be discussed (Hu et al., 2022). New industrial policies and governance measures are necessary to ensure the smooth transition from traditional logistics to ULSs.

Construction. Laws and standards for ULS construction and high-performance equipment manufacturing should be enacted. To meet the needs of system construction under complex geological conditions, specialized engineering solutions and technologies should be applied, such as i) unmanned installation and maintenance technologies of freight pipelines with little interference to existing UUS (Chen, 2018), ii) deep large underground structural design theories, and iii) intelligent methods for urban underground geological detection and measurement.

Operations. A ULS-based city logistics operational platform integrating cutting-edge information technologies (e.g., Internet of Things and blockchain) can be developed to support the whole-process control and management of production, ordering, distribution, and recycling within urban districts. Dedicated techniques for switching ULS operating patterns between normal and emergency states should be developed to ensure that the system can act as an urban lifeline against road supply system disruptions.

Multi-system integration. From a long-term perspective, promoting the integrated deployment and operation of ULSs and other innovative upstream/last-mile logistics measures (e.g., high-speed rail express and parcel drones) is essential. Meanwhile, the collaborative development of ULSs and emerging smart industries, such as digital communities, smart ports, smart industrial parks, digital retail, smart factories, smart warehousing, and smart supply chains, should be encouraged (Feng and Ye, 2021; Wang et al., 2022; Zhen and Li, 2022).

4 Future research directions and topics

4.1 Strategic-level issues

- Case-based analytic and quantified techniques for modeling and calculating the socioenvironmental benefits of underground freight transportation.
- Implementation models for necessity, process feasibility, and efficacy of applying dedicated underground solutions to solve specific city logistics problems, such as the port–city transport conflict.
- Macroscopic interaction mechanisms between ULS and smart city strategies with respect to urban space shaping/reshaping, the enhancement of urban supply resilience, and so on.
- Strategies and implications for the adoption, scope determination, initiation, and dynamic evolvement of ULSs, considering broad system development objectives and barriers.
- An inclusive framework for evaluating the premises (e.g., demand adequacy, economic viability, technology availability, and policy permission), strategic risks, and roadmaps of ULS development.

4.2 ULS and transportation research

- Solving ULS network design problems (e.g., decision making for node location, facility configurations, and topology design and layout) with real-life boundaries (e.g., supply–demand uncertainties, UUS constraints, and multistage system expansion) through advanced mathematical programing and optimization techniques and multisource data fusion.
- Robust design and optimization of heterogeneous underground logistics fleet operating patterns, scheduling tactics, and real-time flow control.
- Spatiotemporal forecasting of ULS business demand based on big data.
- Co-modality structure and organization of surface–underground integrated logistics systems; vertical and horizontal collaborations of ULSs with public transit or other infrastructure.
- Influence of transport policies, top-down transportation planning, and emerging transport technologies on ULS strategies and the implications of ULSs to such aspects.
- Potential changes in traffic behavior, transport modal choice, and user benefits brought about by ULSs.

4.3 ULS and operations management

- Decision support system for new-type urban supply chain operations after ULS introduction, such as vehicle routing, logistics integration, business tracking, underground inventory management, service pricing, distribution resource plans, and so on.
- Smart logistics architecture and common operations management protocols of future cities enabled by ULS infrastructure and disruptive intelligent concepts, such as cyber–physical systems and digital twinning.
- Strategies and value analysis methods for business stakeholders (e.g., third-party logistics service providers, chain companies, and retailers) to incorporate ULSs into their production and operations management systems.
- Approaches for enhancing ULS service performance and operational resilience based on smart information technologies.

4.4 ULS and innovation management

- Significance, enablers, barriers, and countermeasures for the transition from traditional logistics markets and industries to new ULS-based markets and industries.
- Formation and structure of innovation systems, innovation diffusion media, and sociotechnological institutions associated with ULSs; potential paths for establishing and governing ULS innovation ecology under government leadership.
- Investigating market and public attitudes regarding ULS practice and relevant changes and how to promote ULS entrepreneurship and technology innovation through organizational incentives.
- Procedures and key elements of ULS knowledge creation, accumulation, aggregation, application, and platformization.

4.5 ULS and project management

- Organizational complexity theories and cross-organizational behavior mechanisms of mega ULS projects.
- Front-end planning, procurement methods, public–private partnerships, and stakeholder collaborations/competitive networks of ULS projects.
- Basic issues constituting ULS project management body of knowledge (e.g., integration, scope, schedule, cost, quality, risk, and so on).
- ULS project legislation, regulation, governance, and value management.
- Possible application of smart technologies in ULS construction management and infrastructure maintenance.

References

Beijing Municipal Commission of Planning and Natural Resources (2018). Regulatory Detailed Planning of Beijing Municipal Administrative Center (2016–2035). Online Report (in Chinese)

Chen X S (2018). Research on combined construction technology for cross-subway tunnels in underground spaces. Engineering, 4(1): 103–111

Chen Z L, Dong J J, Ren R (2017). Urban underground logistics system in China: Opportunities or challenges? Underground Space, 2(3): 195–208

China State Council (2019). Program of Building China's National Power in Transportation (in Chinese)

Egbunike O N, Potter A T (2011). Are freight pipelines a pipe dream? A critical review of the UK and European perspective. Journal of Transport Geography, 19(4): 499–508

Feng B, Ye Q W (2021). Operations management of smart logistics: A literature review and future research. Frontiers of Engineering Management, 8(3): 344–355

Guo D J, Chen Y C, Yang J S, Tan Y H, Zhang C H, Chen Z L (2021). Planning and application of underground logistics systems in new cities and districts in China. Tunnelling and Underground Space Technology, 113: 103947

Hu W, Dong J J, Hwang B G, Ren R, Chen Z L (2022). Is mass rapid transit applicable for deep integration of freight-passenger transport? A multi-perspective analysis from urban China. Transportation Research Part A: Policy and Practice, 165: 490–510

Management Committee of Xiong'an New Area of China (2021). Controlled Detailed Planning of Rongcheng City Cluster, Xiong'an New Area, Hebei Province. Online Report (in Chinese)

Ministry of Transport of China (2022). The 14th Five-year Plan for China Transportation Science and Technology Innovation (in Chinese)

National Development and Reform Commission (2022). The 14th

Five-year Plan for China's Modern Circulation System Construction (in Chinese)

Qian Q H (2016). Present state, problems and development trends of urban underground space in China. Tunnelling and Underground Space Technology, 55: 280–289

Qian Q H, Guo D J (2007). Introduction to Urban Underground Logistics System. Beijing: China Communications Press (in Chinese)

Swiss Federal Council (2020). FF 2020 8537 Message regarding the Federal Law on Underground Freight Transport (in German)

The ASCE Task Committee on Freight Pipelines of the Pipeline Division (1998). Freight pipelines: Current status and anticipated future use. Journal of Transportation Engineering, 124(4): 300–310

Visser J G S N (2018). The development of underground freight transport: An overview. Tunnelling and Underground Space Technology, 80: 123–127

Wang L, Deng T H, Shen Z J M, Hu H, Qi Y Z (2022). Digital twin-driven smart supply chain. Frontiers of Engineering Management, 9(1): 56–70

Yang H Y, Jiang Y, Li Z, Gao J J, Wang B C (2021). Comprehensive management strategy of underground space development in China. Strategic Study of Chinese Academy of Engineering, 23(4): 126–136 (in Chinese)

Zandi I, Allen W B, Morlok E K, Gimm K, Plaut T, Warner J (1976). Transport of solid commodities via freight pipeline: Cost and level of service comparison, Volume I. First year final report. Report No. DOT-TST-76T-35. Washington, D. C.: Office of University Research, Office of the Secretary, US Department of Transportation

Zhen L, Li H L (2022). A literature review of smart warehouse operations management. Frontiers of Engineering Management, 9(1): 31–55

Zhou Y X, Zhao J (2016). Assessment and planning of underground space use in Singapore. Tunnelling and Underground Space Technology, 55: 249–256