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Using system dynamics to analyze the development of urban freight transportation system based on rail transit: A case study of Beijing

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ABSTRACT

Integrating logistics activities into urban passenger rail transit network (URFT) is regarded as an effective approach to promote urban sustainability and reduce the negative externalities of road-based transportation. This study applied a system dynamics method to simulate URFT system development by focusing on internal operations and external impacts. The characteristics of four major stakeholders (i.e., the government, URFT operator, market, and road freight sector) as well as a series of variables affecting system operations, such as metrics of social and environmental externalities, pricing, investment, and subsidies, were incorporated into two submodels. A case study of Beijing, China was provided to demonstrate the historical validity and rationality of simulation results from 2007 to 2035. Three decision variables (i.e., investment policy, network scale and market competitiveness) were combined into eight distinct scenarios to examine the external benefits, pricing strategies, capital funding structure and business volume of URFT. The findings show that URFT schemes with higher funding and capacity lead to greater reductions in the losses of traffic congestion, air pollution, and accidents. Furthermore, both government support in the early stage and regulation mechanisms among price, supply–demand level, and investment play significant roles in improving the system performance.

1. Introduction

In an era of rapid global urbanization, over half of the world population lives in cities (Bai, 2018), with increasing requirements for commodities, daily necessities, and means of production. Improving the efficiency of the movement of goods to promote sustainable urban development has become a top priority for local governments (Kin, Verlinde, & Macharis, 2017). Logistics activities ensure the freight transportation from upstream gateways, such as ports, rail terminals, logistics parks, and manufacturing facilities to secondary distribution stations, warehouses, and finally inner-city customers and retailers (Cui, Dodson, & Hall, 2015). A prosperous urban logistics market can not only generate huge commercial value and reduce the cost of trade (Dablanc, 2007), but also make a substantial contribution to the competitiveness of industry (Anderson, Allen, & Browne, 2005), which is crucial for socioeconomic growth.

However, the sustainability of this prosperity is difficult to achieve. The externalities of urban freight transport pose threats to human well-being and quality of life, which has triggered numerous green initiatives to mitigate the negative impact of urban freight traffic (Muñoz-Villamizar, Montoya-Torres, & Faulin, 2017). Among them, the concept of incorporating urban goods deliveries into the under-exploited capacity of passenger rail transit networks has attracted wide attention (Behiri, Belmokhtar-Berraf, & Chu, 2018). As a sustainable supplement to the road-based mode, an urban rail-based freight transportation (URFT) system has extensive benefits in terms of eliminating externalities, upgrading logistics reliability (Dinwoodie, 2006), and improving efficiency (Behrends, 2017). In particular, owing to the dual utilization of rail infrastructure, the high cost of system construction can be saved, particularly in underground projects such as metros (Shan, Hwang, & Wong, 2017; Zhao, Hwang, & Yu, 2013). A URFT is easier to implement compared with the dedicated rail logistics systems that have been discussed for many years (Chen, Dong, & Ren, 2017). The sustainability of a URFT system lies in its ability to deal with the contradictions faced by the current road-dominated mode.

Traditional road-based transport causes serious negative externalities for the urban society and environment, including traffic congestion, air pollution, resource consumption, risk, acoustic and

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visual interference, and the deterioration of land use (Russo & Comi, 2016; Sathaye, Harley, & Madanat, 2010). It is estimated that logistics activities account for 20–30 % of urban road resources, but one-third of the total pollution-related damage (Coulombel, Dablanc, Gardrat, & Koning, 2018) and nearly 40 % of urban air pollution and traffic hazards (European Commission, 2011). The adverse effects of this unsustainability, in turn, hinder urban economic growth.

Moreover, passenger and goods vehicles share limited road resources (Lindholm & Behrends, 2012), which is neither sustainable nor economical for urban freight. Policies and measures tend to give priority to protecting passenger transport and restricting freight (Van Rooijen & Quak, 2014), which also conflict with the interests of logistics service providers and customers (Muñuzuri, Cortés, Guadix, & Onieva, 2012). For instance, local authorities must execute strict regulations (e.g., speed limit, congestion charging, and access timetable) to ensure the flow of goods into and out of a city is controlled at a certain level (Chen et al., 2017). Although these mandatory measures might have aided in alleviating traffic congestion, the supply potential of urban logistics systems has been severely confined and the delivery punctuality has been compromised (Holguín-Veras, 2011).

Therefore, the development of urban underground space for freight transport has become a frontier of city logistics. URFT is currently recognized as the most feasible underground freight model (Dong, Hu, Yan, Ren, & Zhao, 2018). Many works in the literature have discussed the great benefits of URFT implementation. However, there is still no systematic and quantitative empirical research on the interaction between URFT and urban freight externalities and how to implement it. Evidently, URFT is a brand-new urban infrastructure system, whose development is inseparable from government-led investment and policy support. Moreover, networked operations are inevitable.

Based on the sustainable freight transport framework proposed by Richardson (2005) and the characteristics of URFT, the aim of this study is to evaluate the potential external and internal performance of a URFT initiative in a dynamic development process with a system dynamics (SD) method. The innovation of this work lies in two aspects: first, a series of key variables for URFT system operations and external impacts were incorporated into the SD model, including the investment and subsidy policy, pricing, supply–demand relations, economics of scale, market competitiveness, congestion, accidents, and air pollution. These variables, which were seldom fully considered in the prior studies, may help to describe and analyze the holistic development mechanism of a URFT system; (ii) Beijing, one of the busiest and most congested cities in China, was taken as a case to simulate the proposed model from a real-world perspective. The modeling and simulation were based on data released publicly by the local government. A similar case was used by Dong, Xu, Hwang, Ren, and Chen (2019) to study the interactive impact of a dedicated underground logistics system (ULS) on the city. We compared our simulation results with theirs. The proposed SD method offers a theoretical framework and modeling path for analyzing the complicated interaction between URFT development and sustainable urban freight transport, and also serves as a scientific reference for addressing the selection of similar green logistics measures and promoting logistics innovation in metropolises.

The rest of this paper is organized as follows. Section 2 presents the state of the art of the relevant literature and the applied urban case. The SD method is described in Section 3, including the structure analysis, data, model formulation, and verification. Section 4 presents the simulation results and offers some policy suggestions. Finally, Section 5 summarizes the main findings of this research.

2. Research background

2.1. City logistics measures and URFT system

Many innovative concepts and technologies have been proposed to develop multimodal and intelligent transportation systems to alleviate the high energy consumption, low efficiency and poor reliability of city logistics (Behrends, 2017). Such as the applications of drones, parcel lockers, and mobile depots in local distribution and last-mile delivery (Kunze, 2016; Vakulenko, Hellström, & Hjort, 2018); electric vehicles (EVs) and urban consolidation centers (UCC) in third-party logistics operations (Allen, Browne, Woodburn, & Leonardi, 2012; Lee, Thomas, & Brown, 2013); as well as buses, taxis, and cargo-bikes in crowd-sourced and shared logistics (Fatnassi, Chaouachi, & Klibi, 2015; Gruber, Kihm, & Lenz, 2014).

However, most of these measures either heavily rely on the roads and labor (e.g., EVs) or suffer from insufficient system capability and applicability (e.g., drones and cargo-bikes), and thus fail to cope with complex freight activities in megacities. It is a consensus that all the behaviors of using road transportation are difficult to substantially improve the negative externalities of freight transportation (Dablanc, 2007; Hu, Dong, Hwang, Ren, & Chen, 2019). For example, EVs and shared logistics increase the requirement of transportation facilities (e.g. charging pile and parking nodes) while reducing exhaust emissions. Parcel lockers and mobile depots improve the distribution efficiency and flexibility, but do not substantially reduce the volume of ground freight. Drones, which do not rely on roads, cannot be used widely because of their low capacity and high levels of noise and visual interference.

The most favorable but challenging solution for city logistics is to shift the midstream goods movement (i.e., flows between suburban logistics centers and inner-city nodes) to a highly automated infrastructure system with a large-scale and high-density network (Lindholm & Behrends, 2012). The concepts of URFT or building a brand-new underground network for freight transportation are the desired alternatives. Different from the aforementioned measures, the logistics system using urban underground space can integrate the whole process of city logistics. As a result, they can produce higher economies of scale and more benefits in the course of massive road–rail model shifts. A dedicated ULS features high risk and high construction cost, and its feasibility of application for urban distribution is still under discussion (Chen et al., 2017). The URFT system, by contrast, has much more potential for implementation and organization, particularly in cities with abundant metro and light rail lines. Moreover, URFT could cooperate with other novel measures, playing a joint role in supplementing and enhancing various urban distribution stages. For instance, a hypothetical combination could be UCC (upstream), URFT (midstream), and EVs (downstream).

URFT has a long history. Its earliest application was in 1927, in London, where an underground mail-rail line was built to move parcels and people (Egbunike & Potter, 2011). The system was demolished after 70-year running period due to obsolescence. Another successful URFT project is under way in the New York City subway network, where a specific subway line is used for transporting municipal waste during idle hours (Cochrane, Saxe, Roorda, & Shalaby, 2016). In Amsterdam, the feasibility of using the metro network to transport goods was investigated, and three patterns of collaborative passenger-and-freight transport were proposed (Strale, 2014). Although the project failed to materialize, the findings have greatly inspired follow-up research. A social survey conducted in Japan has suggested that dual uses of the subway enjoy high public support (Kikuta, Ito, Tomiyama, Yamamoto, & Yamada, 2012). In recent years, the application of ground URFT lines, also known as cargo tram systems, for monoproduct commuting (e.g., daily waste, spare parts, and regular commodities) between suburban factories and inner-city centers has already achieved success in certain European cities, such as Zürich, Dresden, Vienna, and Paris (Cleophas, Cottrill, Ehmke, & Tierney, 2019).

The limitations of urban planning and the complexity of stakeholders' interests are difficulties facing the promotion of rail transit systems for urban freight transport (Browne, Allen, Woodburn, & Piotrowska, 2014). Current research focuses more on URFT planning under realistic constraints. Motraghi and Marinov (2012) proposed a