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Using a multi-objective programming model to validate feasibility of an underground freight transportation system for the Yangshan port in Shanghai

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ABSTRACT

Preventing environmental deterioration and alleviating traffic congestion are becoming urgent problems in urban and transportation planning. Alleviating the pressure from increasing freight transportation traffic via low-emission and innovative transportation methods can reduce problems such as transportation network capacity limits and environmental pollution and contribute to the development of resource-efficient and sustainable cities in the future. Underground freight transportation systems (UFTSs) can improve service quality and transportation efficiency in urban logistics and alleviate traffic congestion and associated problems such as energy consumption and air pollution. Previous studies on urban UFTSs have focused mostly on technical feasibility and policy requirements. Studies providing a quantitative analysis of the effects of introducing a UFTS on an existing transportation network are scarce. In this study, the main goal is to create a quantitative method to analyze the effects of introducing a UFTS on the performance of a transportation network. Thus, a multi-objective programming model of an integrated aboveground-underground transportation network that considers transportation cost, time, and emissions is created. The Yangshan port in Shanghai, China is used as an example to assess whether a UFTS can significantly reduce the cost, time, distance and emissions of the aboveground freight container transportation. The weights on three objective functions are varied to analyze their effects on the solution. These results provide a reference for optimizing freight distribution plans when a UFTS is constructed and for implementing integrated aboveground-underground transportation systems in the future.

1. Introduction

In recent years, rural populations have migrated to cities in increasing numbers, and rising urban populations have led to greater urbanization (Broere, 2016). In 2014, approximately 54% of the global population lived in urban areas. It is estimated that by 2050, this number will have increased to 66% and that the global urban population will have reached 7.4 billion (United Nations, 2014). The rapid increase in urban populations and improvements in living standards are causing a greater demand for transportation. Hence, the number of motorized vehicles in cities is continuously increasing, and road transportation systems are evolving. As an example, automobile ownership in Beijing nearly tripled in one decade from 1.82 million vehicles in 2004 to 5.31 million in 2014.

As urban road transportation systems expand, production and consumption isolation becomes feasible. The increases in international, inter-city, and intra-city logistics and transportation demand have also stimulated economic development (Crainic et al., 2009; Visser et al., 2014). In modern international production, trade, and transportation systems, ports are a critical component in global supply chain networks. Ports are hubs of freight storage, loading, unloading, and transportation, and port logistics are essential (Li et al., 2013; Rodrigues et al., 2015; Song, 2014; Zhang and Zhao, 2015). The port of Shanghai handles the largest volume of shipping containers of any port in China. There are three container port areas: Wusongkou, Waigaoqiao, and Yangshan. The Yangshan port is a deep-water terminal with berth depths greater than 15 m, so it can accommodate the largest container ships. The port is located in the Qiqu archipelago adjacent to Hangzhou Bay, south of Shanghai. The Yangshan port is experiencing high demand for container transportation, while the possibility of expansion via conventional modes such as trucking or rail is low (Ding et al., 2017).

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The Yangshan port accounts for more than one-third of the total throughput of the port of Shanghai, and the throughput will continue to increase in the coming decade. In 2016, Yangshan ranked first in the world in container throughput with a volume of 15.61 million twenty-foot equivalent units (TEUs), and the total container throughput of the port of Shanghai was 36.53 million TEUs. The volume of shipping containers handled by the Yangshan port as a proportion of the total container throughput in Shanghai increased from 15% to 42% in the decade from 2006 to 2016.

To reduce fossil fuel consumption, noise, pollution, and traffic accidents resulting from increased freight transportation, governments in many countries are investigating new, sustainable transportation methods (Machado, 2009; Qian, 2016; Tabesh et al., 2017; Xiao and Konak, 2016). One possibility is alternative container transportation methods, such as the underground freight transportation system (UFTS). A UFTS is a dedicated subterranean rail transportation system using tunnels or pipelines through which any goods can be transported (Vernimmen et al., 2007; Zahed et al., 2017). Compared with trucking, a UFTS has fewer constraints in downtown areas, both legally and geographically.

Previous studies on UFTSs have focused on either technical aspects (Asim and Mishra, 2016; Mueller and Sgouridis, 2011; Rezaeifar et al., 2017; Tabesh et al., 2016) or policy aspects (Janbaz et al., 2017; Marchau et al., 2008; Zahed et al., 2017), with the majority being technically oriented. The technical studies have concentrated on construction methods, vehicle design, cost analyses, transportation routes, and station selection. The policy studies have been mostly feasibility studies involving financial viability and public policy matters. The majority of the studies have focused on construction technology. Few studies have performed a quantitative analysis of the effects of introducing a UFTS on traffic, freight transportation, the environment, and related concerns. However, when used to supplement conventional transportation systems, UTFSs offer advantages.

In this study, a multi-objective programming (MOP) model of an integrated transportation network is used to analyze the feasibility of adding a UFTS at Yangshan and the effects that it would have on container transportation at the port. The freight transportation system is treated as a network, where road transportation is aboveground and the UFTS is underground. Simulations implemented in MATLAB are performed to determine if a UFTS reduces the operational cost, the transportation time, and the emissions.

2. Definition of a UFTS

A UFTS is a freight transportation system using an underground network of tunnels (usually with a diameter exceeding five meters) that allows the automated movement of freight. Because there are fundamental differences in the organization of senders and receivers, a UFTS is also called an underground logistics system.

Over the past 20–30 years, many studies on UFTSs have been conducted (O'Connell et al., 2010; Taniguchi and Heijden, 2000; van der Heijden et al., 2002). As the demand for transportation increases, problems arise in freight transportation and distribution, particularly in high-density urban areas (Najafi et al., 2013). Expansion and improvements of existing systems are not always feasible and do not always bring improvements in efficiency or the environment. More efficient and sustainable transportation systems will be required in the future, and UFTSs have the potential to provide these benefits (Pielage, 2001; Rezaie et al., 2016; Vernimmen et al., 2007).

UFTSs are a form of urban underground transportation, and there are primarily two types: pipe-based and tunnel-based. Pipe-based underground logistics systems include pneumatic, slurry, and capsule types (The ASCE Task Committee on Freight Pipelines of the Pipeline Division, 1998; O'Connell et al., 2008). Capsule-type pipeline systems include hydraulic capsule pipeline (HCP) and pneumatic capsule pipeline (PCP) systems, which differ in terms of the driving medium. Tunnel-based systems generally use automated, guided, electrically propelled vehicles (Ebben et al., 2004; Mueller and Sgouridis, 2011; Vis, 2006). Examples include dual-mode trucks in Japan, automated guided vehicle systems (AGV) in the Netherlands, the CargoCap system in Germany, safe freight trucks in the United States, the CST in Switzerland, and the fast freight system in the United Arab Emirates. Although AGVs were not developed specifically for underground freight transportation, designers of UFTSs can benefit from the experience gained from existing AGV systems (Heijden et al., 2002).

UFTSs have been widely studied. Advances in technology and innovation in urban areas are allowing UFTSs to transit from theoretical studies to actual engineering applications. Although most of the feasibility studies on UFTSs have been qualitative analyses, these studies have not considered integrated aboveground-underground transportation networks. Therefore, their conclusions may be inaccurate and of limited practicality. A detailed analysis of how a UFTS affects an entire freight transportation system is required. In this study, an integrated aboveground-underground freight transportation model was used to quantitatively analyze the effects of a UFTS on container transportation at a large port.

3. MOP model for the integrated transportation network

3.1. Impedance function of roadways

The transportation time of freight at the Yangshan port depends on the number of vehicles traveling on the roads and the physical properties of the roads, such as the length and the width, the road surface quality, and the auxiliary infrastructure. In a port freight transportation network, the road traffic capacity is fixed, and an excessive number of trucks requiring the use of the roads will lead to transportation delays. Therefore, an impedance function for the road network was included in the formulation of the model. A study by the U.S. Bureau of Public Roads (BPR) introduced a function for vehicle transit time that is related to factors such as the traffic capacity of the roads and the unobstructed traffic flow rate. This function has been proved to accurately represent the effect of the traffic volume on the transportation time, so this function has been used in many studies (Corman et al., 2017; Droes and Rietveld, 2015). The road impedance function for aboveground freight transportation can be expressed as follows:

$$t_{ij}^{1} = \frac{d_{ij}}{v_{ij}}\left(1 + \alpha(\frac{q_{ij}}{A_{ij}})^{\beta}\right) \tag{1}$$

where t_{ij}^{1} is the actual time for the freight to transit the road segment (i, j), d_{ij} is the length of the road segment (i, j), v_{ij} is the predefined vehicle speed on the road segment (i, j), q_{ij} is the freight flow on the road segment (i, j), A_{ij} is the rated traffic flow of the road segment (i, j), and α and β are parameters, the values of which were set to 0.15 and 4.0, respectively, based on the values recommended in the USBPR study.

In a UFTS, the freight is moved using automated equipment, so the freight transit time between the surface and underground is fixed. The capacity of the underground logistics system is determined by the freight processing capacity of the station. In this study, the UFTS was assumed to be bi-directional with dual tracks. After the freight is loaded onto the vehicle, the vehicle is dispatched. The inter-station tunnel segment transit time depends on the vehicle speed and the tunnel segment length. Therefore, the impedance function for underground freight transportation is as follows:

$$t_{ij}^{2} = \frac{d_{ij}}{v_{ij}} \tag{2}$$

where $t_{ij}^{2}$is the time required for the freight to transit the tunnel segment.