Using Underground Logistics System to Mitigate the Congestion of Urban Transportation Network

Pengcheng Shang[a], Yicun Chen[*], Guangliang Luo[b], Dongjun Guo[c] and Xiaochao Su[d]

The Army Engineering University of PLA, Nanjing 210007, China.

* Corresponding author:
cyc-lgdx@foxmail.com, [a]s734440309@163.com, [b]guangliang1926@163.com, [c]guo_dogjun@163.com, [d]suxiaochao025@163.com

Keywords: Underground logistics system, road network, network efficiency, equilibrium.

Abstract: Underground logistics system can effectively solve the problem of urban traffic congestion and environmental pollution. Underground logistics system plays an essential role in road network, and the road network is the main transport mode of city logistics. Goods demand between logistics parks affects the city traffic. Meanwhile, urban traffic development promotes the city logistics prosper. Analyzing the effects of underground logistics system on road network is the premise to build the underground logistics system and optimize traffic network. By comparing whether or not established underground logistics system on road network, this paper calculated three indexes including logistics volume, network efficiency and negative effect under the condition of traffic equilibrium with fixed demand to validate the superiority of underground logistics system. Simulation results show that compared with road network without underground logistics system, the road network contained with underground logistics system can greatly improve the network efficiency, reduce ground logistics volume and total logistics disutility, and optimize the transportation network structure to response the variations in logistics demand with emergency at the same time.

1. Introduction

In the search of better life and development, more and more people are migrating from rural area to city, leading to the expansion of urbanization and urban population [1]. Global urban population is 4 billion in 2013 and will be reached 5 billion in 2030 [2]. In order to meet the demand of city life and economic development, city logistics demand is growing [3]. City logistics is different from the industrial logistics on account of its running time calculation counts in hours or even minutes, shorter delivery time means more satisfied evaluation from the customers [4]. Van is the main way of city logistics with large freight volume and frequently delivery times which makes the urban traffic congestion and environmental deterioration [5]- [7]. Due to traffic problem is serious in metropolis particularly, urban development is plagued and needed to ease congestion urgently.

With the automatic transportation and tunnel construction technology development, the researches of underground logistics system (ULS) are gradually taken seriously by many developed countries due to the potential ability to solve traffic problems. ULS refers the logistics transport based on underground pipes or tunnels as the fifth kind of transportation and supply system [8]- [10]. ULS can mitigate the urban traffic and free up ground space, and meets the requirements of sustainable development at the same time. Many researchers investigated the ULS from the technology feasibility, economy feasibility and network planning [11]- [15]. The above works were largely based on qualitative analysis. To date, the quantitative analysis the effects of ULS on the congestion of urban transportation network is rarely reported.

Analysis the effects of ULS on transportation network is the premise to build ULS and optimize traffic network. Adopted appropriate network assessment measure methods are essential to evaluate transportation network [16]. Road traffic flow and network efficiency and network total disutility are three important indexes to evaluate the network, which can support to measure the significance of network element and understand the influence of element to network efficiency and robustness [17]. Therefore, the above three indexes are utilized to analyze the effects of ULS on transportation network in paper.

For quantitative analyzing the effects of ULS on urban transportation network, a transport network between logistics parks in Nanjing is used for exploratory research. We conducted simulation experiments in MATLAB to test the three indexes. By comparing the situations whether or not ULS has exist in traffic network, the validity of ULS to mitigate the congestion is verified.

2. Modeling and simulation

2.1. Logistics Network Equilibrium Model

We selected road network model combined with characteristics of ULS under the fixed demand to analyze the effects of ULS on transportation network in equilibrium condition. We assumed the transportation network only affect by the variation of logistics volume on road. For a given logistics transportation network, the mathematical programming model can be expressed as:

$$\text{Min } Z(x) = \sum_{(i,j)\in E} \int_0^{x_{(i,j)}} t_{(i,j)}(y)dy \tag{1}$$

$$s.t. \quad \sum_{p_k \in P} l_{(i,j)}^{p_k} = x_{(i,j)}, \quad \forall (i,j) \in E \tag{2}$$

$$\sum_{j\in N, j\neq o} x_{(i,j)} = \sum_{w\in W} d_w \delta_{iw}, \quad \forall w \in W \tag{3}$$

$$\int_0^{x_{(i,j)}} t_{(i,j)}(y)dy \le A_{(i,j)} \tag{4}$$

$$l_{(i,j)}^{p_k} \ge 0, \quad \forall (i,j) \in E, p_k \in P \tag{5}$$

where N is a set of logistics parks in logistics network; E is a set of roads between logistics parks in network; i and j are different logistics parks, respectively; $t_{(i,j)}$ is the logistics time impedance at road $(i,j)\in E$ between logistics park i and j; Z is the network total disutility; W is a set of the origin and destination (O-D) demand w; P is a set of delivery path p_k; $l_{(i,j)}^{p_k}$ is logistics volume at road (i,j) belongs to p_k; $x_{(i,j)}$ is the total logistics volume at (i,j); x is set of $x_{(i,j)}$; d_w is value of w; δ_{iw} was set to 1.0 when the origin of the w is i, otherwise δ_{iw} is equal to 0; $A_{(i,j)}$ is the maximum disutility of government expected at (i,j).

Frank-Wolfe algorithm was used to solve the Logistics network equilibrium model, the detailed calculation process as shown in [18].

2.2. Logistics Time Impedance Function

The Bureau of Public Road (BPR) was proposed BPR function in 1964 and widely used in many researches, which can reveal the influence of traffic load on transport time cost [19]. BPR function indicates that transport time cost is related to the traffic capacity and free flow time of the road. In the logistics transport network, free flow time is determined by cargo turnover, transfer and queue time. Therefore, this paper proposed the logistics time impedance function is divided into three sections in the network, including the initial transport time impedance, the logistics park node impedance and the path impedance of three parts, which can be calculated as:

$$t_{(i,j)}^f = \frac{D_{(i,j)}}{v_{(i,j)}} \tag{6}$$

$$t^{c}_{(i,j)}=\begin{cases}0, & x_{(i,j)}<c_{(i,j)}\\ \dfrac{x_{(i,j)}-c_{(i,j)}}{c_{(i,j)}}A, & c_{(i,j)}\le x_{(i,j)}\le c_{\max(i,j)}\\ \dfrac{c_{\max(i,j)}-c_{(i,j)}}{c_{(i,j)}}A+\dfrac{x_{(i,j)}-c_{\max(i,j)}}{c_{(i,j)}}B, & x_{(i,j)}>c_{\max(i,j)}\end{cases} \tag{7}$$

$$t^{t}_{(i,j)}=t_{num}\cdot h \tag{8}$$

$$t_{(i,j)}(x_{(i,j)})=(t^{f}_{(i,j)}+t^{c}_{(i,j)}+t^{t}_{(i,j)})\left[1+\alpha\left(\frac{x_{(i,j)}}{c_{\max(i,j)}}\right)^{\beta}\right] \tag{9}$$

Where $t^{f}_{(i,j)}$ is the initial transport time impedance of road (i,j), which represents the free flow time and follows the equation $t^{f}_{(i,j)}=t^{f}_{(j,i)}$; $t^{c}_{(i,j)}$ is the logistics park node impedance of road (i,j), which represents the cargo turnover time cost and queue time; $t^{t}_{(i,j)}$ is the path impedance transfer of road (i,j), which represents the costs of transfer; $D_{(i,j)}$ and $v_{(i,j)}$ are cargo transport distance and velocity between logistics park i and j, respectively; $c_{(i,j)}$ and $c_{\max(i,j)}$ are the rated and ultimate capacity of road (i,j), respectively; A and B are the congested and queue coefficient, respectively; t_{num} and h are the times and time cost of the transfer from ULS to ground road; α and β are the regression parameters of BPR, respectively.

2.3. Case Setup and Simulation

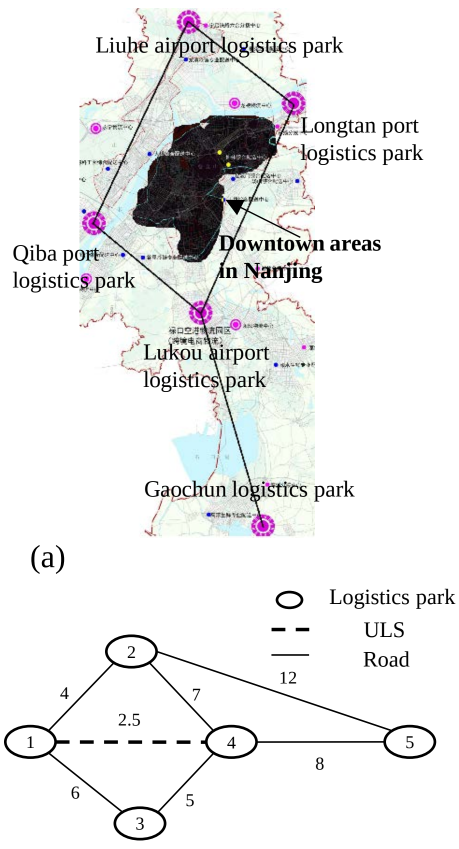

Figure 1. The logistics network in Nanjing: (a)The layout of the logistics parks; (b)The structure of logistics network combined with ULS.

We selected the logistics network in Nanjing to analyze the effects of ULS on urban transportation network, which including five logistics parks such as Liuhe airport logistics park, Longtan port logistics park, Qiba port logistics park, Lukou airport logistics park and Gaochun logistics park. The layout of the five logistics parks as shown in Fig. 1(a). Due to traffic congestion and trucks forbidden in downtown, the direct route between logistics park 1 and 4 does not exists. The six road segments are $(1,2)$, $(1,3)$, $(2,4)$, $(2,5)$, $(3,4)$ and $(4,5)$ between logistics parks, respectively. Three path exists in Nanjing logistics network are $p_1 = \{1,3,4,5\}$, $p_2 = \{1,2,4,5\}$ and $p_3 = \{1,2,5\}$, respectively.

According to the benefits of ULS compared to the road transport, the CargoCap system from German is supposed to be built between logistics park 1 and 4 to analyze the effects on urban transportation network. CargoCap system as one of the ULS was invented in 1998 [20]. CargoCap system is an automatic guided vehicle (AGV) and can operate 24 hours a day in any climate under the condition of unmanned in underground pipe line with the diameter approximately 2 m. The constant speed of CargoCap system was 36 km/h. Considering the trade secret requirement of logistics enterprises and demand of experimental analyze, the coordinates data through tiny modified for five logistics parks are shown in Table I. According to the truck load capability and transportation capability of CargoCap system, the normalization of distance between logistics parks was adopted to obtain the logistics network structure, as shown in Fig. 1(b). The initial transport time impedance and rated capacity of each road (i, j) are shown in Table II. We assumed the ultimate capacity $c_{\max(i,j)}$ is equal to 1.5 times $c_{(i,j)}$. By conservative estimated and integrated into account the operation time and efficiency of CargoCap system, the value of $t^f_{(1,4)}$ was set to 2.5 compared with origin value 9.

Table.1. To format a table caption, use the Microsoft Word template style.

Logistics Park Number	**Logistics Park**	**Coordinates of Logistics Park**
1	Liuhe airport logistics park	(510,1639)
2	Longtan port logistics park	(848,1378)
3	Qiba port logistics park	(207,994)
4	Lukou airport logistics park	(550,706)
5	Gaochun logistics park	(750,22)

Table.2. Value of the Initial Impedance $t^f_{(i,j)}$ and Rated Capacity $c_{(i,j)}$

Node	**Road**						**ULS**
	(1,2)	**(1,3)**	**(2,4)**	**(2,5)**	**(3,4)**	**(4,5)**	**(1,4)**
$t^f_{(i,j)}$	4	6	7	12	5	8	2.5
$c_{(i,j)}$	10	10	10	10	10	10	40

Table.3. Parameters of the transport network simulation

Network	G_R	$G_{ULS\text{-}R}$
P	1,3,4,5 1,2,4,5 1,2,5	1,3,4,5 1,2,4,5 1,2,5 1,4,2,5
A	2	2
B	5	5
α	0.15	0.015
β	4	4
h	0	0.5

We conducted a variety of simulation experiment scenarios in MALTAB to test the effects of ULS on transportation network under the fixed demand. Each scenario under the same demand w are divided into two networks G_R and G_{ULS}. G_R is the network only exists road transportation without ULS and G_{ULS} is the network exists road transportation with the addition of ULS. For simplicity, only a O-D demand is considered in this paper and the variables in this paper are normalized. The parameters of the transportation network G_R and G_{ULS} are shown in Table 3.

2.4. Network Efficiency Evaluation Method

In order to quantify the average goods transport efficiency between logistics parks in the transportation network G_R and G_{ULS}, the network average efficiency GE was used to calculate the efficiency of network generally, and can be calculated as:

$$GE = \frac{1}{\frac{1}{2}N(N-1)} \sum_{i>j} \frac{1}{d_{ij}} \tag{10}$$

where d_{ij} is the shortest path between logistics park i and j in transportation network.

However, a basic feature that the value of a reasonable network efficiency evaluation index is inversely proportional to the total network disutility under fixed demand[16]. For reflecting the effects of road time impedance on the network efficiency, we selected index ε to evaluate the network efficiency when the network was achieved equilibrium, which can be calculated as:

$$\varepsilon = \frac{1}{n_e} \sum_{i \neq j} \frac{\bar{x}_{(i,j)}}{\int_0^{\bar{x}_{(i,j)}} t_{(i,j)}(y)dy} \tag{11}$$

where n_e is the number of road which passed by goods; $\bar{x}_{(i,j)}$ is the logistics volume on the road (i,j) at the network achieved equilibrium.

3. Result analysis and discussion

3.1. The Effects of ULS on Road Logistics Volume

In this paper, we investigated the effects of ULS on road logistics volume by changing the O-D demand (1, 5). Taking the O-D demand $d_w = 60$ as an example, the logistics volume $x_{(1,2)}$ decreases from 32.93 in network G_R to 19.46 in network G_{ULS}, the logistics volume $x_{(2,4)}$ drops from 3.61 in network G_R to 0 in network G_{ULS}, which are shown in Fig. 2. The logistics volume $x_{(1,2)}$ and $x_{(2,4)}$ decreased by 40.91% and 100%, respectively. With the increasing of O-D demand d_w, the increment of logistics volume $x_{(1,2)}$ is the highest in the network G_R, which significantly exceed the increment of logistics volume in network of G_{ULS}. Taking the experiments $d_w = 60$ and $d_w = 180$ to compared, a 295.3% increase in the logistics volume $x_{(1,2)}$ in network G_R while 245.6% increase in network G_{ULS} with the demand of O-D (1, 5) increased by three times. Therefore, the ULS can reduce the road logistics volume to mitigate traffic congestion significantly and response to the emergency increase of traffic demand effectively.

Using ULS not means reducing logistics volume in all roads. Taking $d_w = 60$ as an example, the logistic quantity $x_{(2,4)}$ increases from 0 in network G_R to 9.16 in network G_{ULS}. Due to the majority of total logistics volume pass through the downtown by ULS to reach the logistics park 4, the network will distribute the logistics through the road segment $(4,2)$ to prevent the road $(4,5)$ congestion. From the perspective of preventing urban traffic congestion, the load capacity of roads are used rationally can optimize the transportation network structure and benefit to urban traffic.

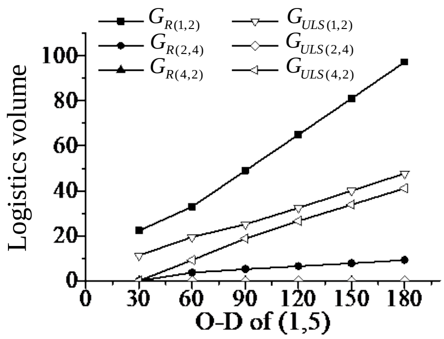

Figure 2. The logistics volume in G_R comparison with G_{ULS}

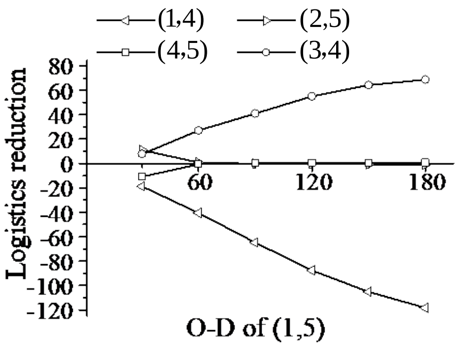

Figure 3. The logistics reduction in segments from network G_R to G_{ULS}

ULS will serve as the main logistics transport channel to deliver goods in urban transportation network. The curve of road logistics volume reduction in network G_R compared to network G_{ULS} which vary with the demand d_w are shown in Fig. 3. The underground logistics volume $x_{(1,4)}$ in network G_{ULS} grows with the increase of d_w. Taking the O-D demand $d_w = 90$ as an example, the underground logistics volume of $x_{(1,4)}$ is 64.84 and accounting for the total demand of 72.04%,. Which contributes to 40.98 reduced of road logistics volume $x_{(3,4)}$ in network G_{ULS}. Taking the O-D demand $d_w = 180$ as an example, the underground logistics volume of $x_{(1,4)}$ is 118.25 and accounting for the total demand of 65.70%,. Which contributes to 68.77 reduced of road logistics volume $x_{(3,4)}$ in network G_{ULS}. By using ULS in transportation network, ULS will serve as the main logistics transport channel and the majority of logistics volume will be transferred to the underground. The tiny reduction of logistics volume in $x_{(4,5)}$ and $x_{(2,5)}$ are opposite due to the characteristics of the logistics transportation network.

3.2. The Effects of ULS on Transportation Network Efficiency

In order to investigate the effects of ULS on traffic network, the road time impedance is utilized to calculate the total logistics disutility $Z(x)$ and the network efficiency ε is used to evaluate the transport efficiency of urban traffic network. The comparison of network efficiency ε and total logistics disutility $Z(x)$ between network G_{ULS} and network G_R are shown in Fig. 4. For the network G_R, the network efficiency ε_{G_R} decreases and the total logistics disutility Z_{G_R} increases with the increase of the demand d_w. By adopting the ULS from logistics park 1 to 4, the decrease trend of network efficiency and increase trend of total logistics disutility are obviously lower in the network G_{ULS} compared with the network G_R.

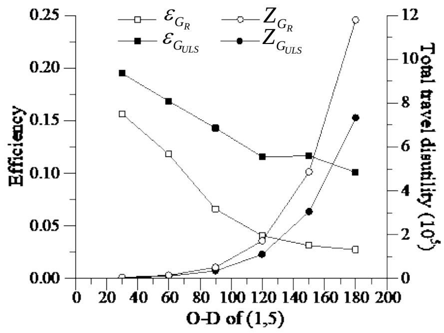

Figure 4. Network efficiency and disutility in G_R comparison with G_{ULS}

Using ULS in transportation network can improve the network efficiency and reduce the total logistics utility. Compared with the logistics network G_R, the network efficiency is higher and the total logistics disutility is lower in network G_{ULS}. Taking the scenario of O-D demand (1,5) $d_w = 120$ as an example, the network efficiency ε_{G_R} is 0.04, and the network efficiency $\varepsilon_{G_{ULS}}$ is 0.12, which three times larger than ε_{G_R}. The total logistics disutility Z_{G_R} is 17178.67, while the $Z_{G_{ULS}}$ is only 11040.02 and equals to 64.27% of Z_{G_R}. Therefore, the establishment of ULS can significantly improve the efficiency of existing urban transportation network and reduce the total disutility.

4. Conclusions

As a significant means to solve urban traffic congestion, environmental pollution and "bottleneck" problem of logistics industry, the ULS is a new method and concept to solve urban traffic problem. In this paper, the logistics network including five logistics parks in Nanjing was adopted as an example to compare the pros and cons of whether or not established ULS. The influences of ULS on the urban road network were quantitatively analyzed by calculating the logistic quantity, network efficiency and total logistics disutility of the traffic network under fixed demand. Through the simulation experiments in MATLAB, the results show that compared with the road network without ULS, the road network contained with ULS can greatly improve the network efficiency, reduce ground logistics volume and total logistics disutility, and optimize the transportation network structure to response the variations in logistics demand with emergency at the same time.

Acknowledgments

This study was supported by the State Key Program of National Natural Science of China (Grant No. 71631007).

References

[1] W. Broere, "Urban underground space: solving the problems of today's cities," Tunneling and Underground Space Technology, vol. 55, pp. 245–248, 2016.

[2] N. Anand, R. V. Duin, H. Quak, and L Tavasszy, "Relevance of city logistics modelling efforts: a review," Transport Reviews, vol. 35, no. 6, pp. 701–719, 2015.

[3] V. Marchau, W. Walker, and R. V. Duin, "An adaptive approach to implementing innovative urban transport solutions," Transport Policy, vol. 15, no. 6, pp. 405–412, 2008.

[4] Y. Liu, K. He, J. Liu, and Y. Xu, "Analysis of the concept of urban rail transit based city logistics system," in 2008 International Conference on Smart Manufacturing Application, IEEE, 2008, pp. 288–292.

[5] M. Lindholm and S. Behrends, "Challenges in urban freight transport planning – a review in the Baltic Sea region," Journal of Transport Geography, vol. 22, no. 2, pp. 129–136, 2012.

[6] T. T. Taefi, J. Kreutzfeldt, T. Held, and A. Fink, "Supporting the adoption of electric vehicles in urban road freight transport – a multi-criteria analysis of policy measures in Germany," Transportation Research Part a-Policy and Practice, vol. 91, pp. 61–79, 2016.

[7] A. M. Zanni and A. L. Bristow, "Emissions of CO2 from road freight transport in London: trends and policies for long run reductions," Energy Policy, vol. 38, no. 4, pp. 1774–1786, 2010.

[8] O. Huang, D. Guo, and Z. Chen, "Design of the distribution center of underground logistic system with SLP method," Chinese Journal of Underground Space and Engineering, vol. 2, pp. 1–4, 2006.

[9] O. N. Egbunike and A. T. Potter, "Are freight pipelines a pipe dream? A critical review of the UK and European perspective," Journal of Transport Geography, vol. 19, no. 4, pp. 499–508, 2011.

[10] M. Ebben, D. J. V. D. Zee, and M. V. D. Heijden, "Dynamic one-way traffic control in automated transportation systems," Transportation Research Part B: Methodological, vol. 38, no. 5, pp. 441–458, 2004.

[11] B. Vernimmen, W. Dullaert, E. Geens, T. Notteboom, B. T'Jollyn, W. V. Gilsen, and W. Winkelmans, "Underground logistics systems: a way to cope with growing internal container traffic in the port of Antwerp?" Transportation Planning and Technology, vol. 30, no. 4, pp. 391–416, 2007.

[12] G. Arends and E. D. Boer, "Tunneling of infrastructure: from non-considered to Ill considered – lessons from the Netherlands," Tunneling and Underground Space Technology, vol. 16, no. 3, pp. 225–234, 2001.

[13] I. Docherty, "Transport and regional economic competitiveness in the global economy," Journal of Transport Geography, vol. 12, no. 4, pp. 341–342, 2004.

[14] C. G. Forero, A. Maydeu-Olivares, and D. Gallardo-Pujol, "Factor analysis with ordinal indicators: a Monte Carlo study comparing DWLS and ULS estimation," Structural Equation Modeling A Multidisciplinary Journal, vol. 16, no. 4, pp. 625–641, 2009.

[15] D. H. M. C. Van, et al., "Using simulation to design an automated underground system for transporting freight around Schiphol airport," Interfaces, vol. 32, no. 4, pp. 1–19, 2002.

[16] Q. Jin, F. Shi, L. B. Deng, and L. W. Xiao. "Quantitative evaluation method for road transportation network efficiency and its application," Journal of Jilin University, vol. 40, pp. 47–51, 2010.

[17] H. Y. Yin and L. Q. Xu, "Measuring the structural vulnerability of road network: a network efficiency perspective," Journal of Shanghai Jiaotong University (Science), vol. 15, no. 6, pp. 736–742, 2010.

[18] M. Fukushima, "A modified Frank-Wolfe algorithm for solving the traffic assignment problem," Transportation Research Part B: Methodological, vol. 18, no. 2, pp. 169–177, 1984.

[19] H. Youn, M. T. Gastner, and H. Jeong, "Price of anarchy in transportation networks: efficiency and optimality control," Physical Review Letters, vol.101, no. 12, pp. 128701, 2008.

[20] B. J. Pielage and J. C. Rijsenbrij, "Developments in underground freight transportation," Edward Elgar Publishing, pp. 65–84, 2005.