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The impact of metro-based underground logistics system on city logistics performance under COVID-19 epidemic: A case study of Wuhan, China

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ABSTRACT
The global outbreak of COVID-19 has further exposed deficiencies in city logistics based on human and ground roads, such as poor emergency response capacity and high risk of infection during transportation. Metro-based underground logistics system (M-ULS) may be an innovative approach to deal with this city-level disaster due to its efficient operation, contactless and driverless characteristics. However, the market evolution process and the quantitative calculation framework of comprehensive benefits after the application of M-ULS are still unclear, which has become a problem of mutual restriction with the extensive application of M-ULS. This paper attempts to use the system dynamics method, based on the real-world simulation, to analyze the quantitative relationship between the M-ULS implementation and the city logistics performance under epidemic outbreaks. Wuhan city in China was selected as the empirical background, and five simulation scenarios were set under different implementation strategies of M-ULS in response to the epidemic. Six variables were selected to measure city logistics performance and M-ULS operation status, including demand fill-rate, unit delivery time, total deprivation cost, total transportation cost, total number of susceptible people, and utilization rate of M-ULS. The results show that M-ULS is effective in improving the performance of city logistics and responding to the epidemic. The delivery time and transportation cost have a strong impact on the market share of M-ULS. Finally, a set of incentive policies was designed to promote the adoption of M-ULS. The findings not only provide a method for evaluating the overall performance of M-ULS, but also provide a unique perspective for promoting the implementation of M-ULS and responding to the transportation challenges brought by the epidemic.

1. Introduction
Corona Virus Disease 2019 (COVID-19), with its global outbreak and unpredictable duration, has exerted a huge impact on urban development and residents’ life in all aspects. The logistics industry, especially city logistics, has been seriously damaged, such as the serious lack of distribution personnel, the sharp rise in cost, increased inspection and quarantine links. Blockades and quarantines multiplied panicked residents’ demands for supplies and door-to-door services, making it difficult to meet the city’s basic needs with sharply reduced logistics supplies. More significantly, delivery personnel are at high risk of contracting the virus. For example, during the closure of Wuhan city, 43% of the delivery personnel experienced fever (The Paper, 2020a). Therefore, in the face of the epidemic and the potential large-scale urban emergency in the future, the reform of high-manpower urban transportation mode to develop contactless smart city logistics system has been put on the urgent agenda.

Underground logistics system (ULS) has been widely recognized as an effective means for sustainable urban freight transport (Visser, 2018). Among the different forms of ULS, metro-based underground logistics system (M-ULS) has received widespread attention due to its low construction cost and high feasibility (Zhao et al., 2018). Independent underground operation environment and flexible freight organization process can effectively improve the efficiency of city logistics (Hu et al., 2020a). Non-contact freight process can perfectly fit the urban transport demand under the epidemic situation, and greatly reduce the risk of virus transmission in the transportation process (Hu et al., 2020b).

Covid-19 has become another important driver for the widespread
implementation of M-ULS and ULS. Until this year, their practice had not been plain sailing, with high cost and other factors hampering the development of underground transportation (Cochrane et al., 2017). Nor is there a reasonable benefit framework to support a reasonable assessment of the overall performance of the ULS (Chen et al., 2017). Combined with the transport market conditions under the epidemic, quantitative analysis of the overall benefits of M-ULS will help deepen the understanding of urban decision-makers on the value of M-ULS and also provide a unique insight to solve the transport problems during the epidemic.

Analyzing the performance of M-ULS is a challenging task. On the one hand, the benefits assessment of M-ULS requires the comparison of multiple scenarios such as normal situation, epidemic outbreak and M-ULS implementation. On the other hand, market factors such as demand, average transportation cost, and delivery time determine the market share of M-ULS (Hu et al., 2020b). In particular, restrictive and incentive policies dynamically affect supply and demand in the freight market, which makes modelling more difficult (Cui and Nelson, 2019). In short, the simulation of the M-ULS includes nonlinear and dynamic behaviors and feedbacks among multiple stakeholders in multiple scenarios.

This paper aims to answer two research questions: What are the effects of the M-ULS implementation in the city logistics performance under epidemic outbreaks? and what is the development process of M-ULS in the context of epidemic? Based on the real-world data of Wuhan city in China during the period of high outbreak of the epidemic, the operation status and implementation effectiveness of M-ULS were analyzed by system dynamics (SD) method. Key factors affecting the freight market, such as blockade measures and financial subsidies to M-ULS, were also included in the modeling process. Then, a phased policy framework was proposed to facilitate the application of M-ULS and to address the transportation challenges posed by the COVID-19 epidemic.

The innovation lies in two aspects. First, M-ULS was introduced as a unique means to try to break through the plight of city logistics under the COVID-19 epidemic, which also provided a new driver for the practice of M-ULS. Second, a set of effective macro-micro incentive policies were established to promote M-ULS, so as to provide effective support for decision-makers to deal with city logistics issues.

The remainder is structured as follows: Section 2 reviews the state of the art of the relevant literature; Section 3 proposes how the SD method is applied to analyze the impacts of M-ULS on city logistics; Section 4 discusses the key findings; and finally, Section 5 presents the conclusions and avenues for future research.

2. Literature review

2.1. City logistics under epidemic outbreaks

The dilemma of city logistics is becoming particularly prominent during the epidemic outbreaks. On the one hand, the limited workforce inevitably leads to the delivery delay, and the scarcity of necessities brings huge deprivation cost to the residents (Holguín-Veras et al., 2013; Singh et al., 2020). In particular, with a surge of online shopping, door-to-door deliveries also skyrocket, thus weighing more burden on goods distribution (Sheth, 2020). On the other hand, with the sharp rise in operating cost, the logistics companies are struggling to survive the epidemic outbreaks (Ivanov, 2020). For instance, it was reported that the salaries of freight drivers rose about three times during COVID-19 outbreaks (The State Council Information Office of PRC, 2020). More importantly, the epidemic has exacerbated the infection risk of distribution personnel, further reducing the available workforce (Lemke et al., 2020). Generally, the current city logistics system cannot effectively respond to the threat of a pandemic outbreak like COVID-19.

Traditionally, the literature on city logistics under epidemic outbreaks has mostly focused on the humanitarian logistics issues, such as the location of temporary distribution facilities, relief distribution strategies, transport policy-making, etc (Dasaklis et al., 2012). A series of indicators, such as demand fill-rate, delivery time, deprivation cost and transportation cost, have been put forward to analyze the city logistics performance in terms of effectiveness and efficiency (Huang et al., 2015; Banomyong et al., 2019). However, few studies have analyzed the impacts of epidemic outbreaks on commercial logistics, which cannot provide an effective decision-support framework for solving the problems of commercial products transportation. In addition, the previously studied cases, such as SARS, Ebola and Influenza, have regional characteristics and the city logistics problems exposed have not yet aroused wide resonance (Queiroz et al., 2020). However, during COVID-19 outbreaks, serious city logistics issues are prevalent on a global scale. Moreover, the research on the epidemic transmission risk during transportation remains a blind spot. While the recent work of Yu et al. (2020) has analyzed the number of susceptible people in the transportation process, it mainly focused on the transport of medical waste rather than the commercial product. Hence, it is urgent to systematically analyze the impacts of epidemic outbreaks on the city logistics performance and develop highly intelligent and contactless urban freight transport modes.

2.2. State-of-the-art research of M-ULS

The basic idea of the M-ULS is to directly transport goods from the out-of-town logistics parks, warehouses, factories or consolidation centers to downtown areas via the retrofitted subway system (Hu et al., 2020a). The final customers of M-ULS service, namely the users of M-ULS, include third-party logistics carriers, hypermarkets, enterprises, hospitals, households, etc. M-ULS, as a special form of ULS, is similar to other forms of ULSs in terms of network planning, system operation and benefit analysis (Chen et al., 2017). Currently, the research of M-ULS has covered the whole transportation process including freight volume forecasting, packing strategies, train scheduling, freight allocation and transportation, etc.

2.2.1. Feasibility of M-ULS

The feasibility of M-ULS has already been analyzed on many national projects in Italy, Japan, England, France, China, Netherlands and America, respectively (Egbunike and Potter, 2011; Kikuta et al., 2012; Motraghi and Marinov, 2012; Cochrane et al., 2017; Ozturk and Patrick, 2018; Zhao et al., 2018; Gatta et al., 2019). The cost-benefit analysis illustrates that M-ULS exhibits huge advantages in delivery time and transportation cost, compared with traditional ground transportation (Visser, 2018). The implementation of networked M-ULS can also promote sustainable urban development and reduce the negative externalities of city logistics (Dong et al., 2018, 2019). According to Hu et al. (2020a), the Beijing M-ULS project can reduce the transportation-related emissions of CO$_2$ and NO$_x$ by 4.52 million tons and 18.37 thousand tons during 2021–2035. Similarly, the results of Dong et al. (2019) indicates that the emissions of PM are reduced by 64.2% with the application of ULS in Beijing. However, few studies have analyzed the impacts of M-ULS implementation on the city logistics performance under the emergencies such as COVID-19 outbreaks. In addition, while M-ULS will replace jobs of truck drivers as with other forms of driverless transportation mode, the development of M-ULS will create many new jobs in a variety of fields, such as manufacturing of automatic logistics equipment and operation of smart logistics (Chen et al., 2017). As for the technical feasibility, great progress has been made in the vehicle automation design, advanced equipment manufacturing, intelligent control and other aspects of M-ULS. The key technologies matching the operation of the subway system have fully met the implementation requirements (Shahboeei et al., 2019). The current underground engineering construction technology can also greatly alleviate the negative impacts of M-ULS construction on the operation of the subway system.
2.2.2. System operation of M-ULS

M-ULS can realize intelligent operation in the whole process of freight transport. Referred to Hu et al. (2020a), the operation process of M-ULS is illustrated in Fig. 1. Goods are transported by driverless freight trains in the subway tunnels and then distributed and transferred within the M-ULS network to reach the terminal nodes. Finally, goods can be delivered to customers in a variety of forms, such as automated guided vehicles, self-service cabinets and drones, or manual delivery, combined with the ground conditions and specific needs. The M-ULS operator will adjust the freight scheduling appropriately based on the real-time conditions in the freight market.

Past ULS projects, such as the London Mail Rail System and OLS-ASG, have provided invaluable experience for the M-ULS implementation. On the one hand, the lack of clear and sustained policy support is one of the important reasons for the failure of ULS projects (Visser, 2018). However, the current policy and research are merely advocacy and encouragement, do not go deep into the operational, coordinated and phased implementation level. On the other hand, many ULS projects only serve dedicated purposes, i.e., the transport of flower or letters and parcels, which not only weakens the flexibility of ULS, but also fails to generate huge benefits to attract users (Egbunike and Potter, 2011).

The government’s financial support, such as infrastructure investment and operating subsidies, is conducive to promoting the networked operation of M-ULS and realizing the economic sustainability of the system (Zheng et al., 2020). The policy system of sustainable logistics development can also provide some enlightenment for the incentive policies of the M-ULS, and some can even directly apply to or guide the implementation of M-ULS. The widely implemented measures, such as taxation, travel restriction policies and environmental regulatory policies, have great effects on promoting the development of green logistics (Van Hassel, 2016; Park et al., 2016; Holguín-Veras et al., 2018; Vanelslander et al., 2019). However, a systematic policy support framework for the M-ULS implementation has not been established. In particular, a set of city logistics emergency strategies that effectively coordinate M-ULS operation and ground logistics have not been developed to address the threat of COVID-19 outbreaks and other future emergencies. Of course, unclear benefits analysis also hinders the policy formulation.

3. Methodology

SD method, originally developed by Forrester (1958), can combine both the qualitative and quantitative analysis to understand the complex systems with inherent dynamics, i.e., the system performance evolves over time and depends on feedback loops. Compared with other management science methods, the advantages of SD model are prominent. On the one hand, the variables of the SD model vary over time based on the feedback mechanism of the system, which is conducive to simulating the long-term and periodic problems (Mingers and White, 2010). On the other hand, the data needed in the modeling process is easily accessible, and can be obtained from a variety of sources, such as statistics, literature, and even people’s experience (Puyllaert et al., 2018). Therefore, this paper adopted SD method to analyze the role of M-ULS in breaking the bottleneck of city logistics, and further to explore the government’s response mechanism to transportation difficulties during the epidemic outbreaks.

SD is widely used in the field of city logistics, such as transportation policies analysis and innovative transportation simulation (Lewe et al., 2014; Sabounchi et al., 2014). According to Sterman (2000), an SD model was established, and the analysis steps as shown in Fig. 2 were carried out.

First, the background of the case was analyzed to propose the basic parameters and assumptions for the SD model. Then, the system boundary was defined to identify the main variables included in city logistics. Thus, the causal loop diagram (CLD) and the stock-flow diagram were established to describe the relationships between the main variables. Next, we validated the model and simulated the scenarios. Finally, the simulation results were discussed in combination with the M-ULS operation strategies and the transportation policies to propose the coping mechanism.

3.1. Empirical background analysis

The real urban and logistics data of Wuhan Central Activity Area (CAA) were selected as the empirical background. CAA covers an area of 530 square kilometers and had a population of 6.1 million in 2019, accounting for 54.5% of the city’s population (Wuhan Municipal Bureau Statistics, 2020). It is an area with high population density, reaching 11,510 people per square kilometer. The city’s freight volume was 417.8 million tons in 2019 (Wuhan Municipal Bureau Statistics, 2020). Based on the bubble weight ratio, the delivery volume had reached 92.7 billion pieces, about 23 pieces per person per day. According to Hu et al. (2020b), 20%–25% of the total freight is consumer goods, and the number of parcels per person is as high as five pieces per day. Normally, there are more than 30,000 couriers and 50,000 trucks are involved in the city’s logistics, so the urban transport is under great pressure and transportation disruption often occurs (Wuhan Municipal Bureau Statistics, 2020).

The COVID-19 outbreak in 2020 has had a huge impact on Wuhan’s transportation and logistics. In response to the changes in the epidemic, local governments have implemented various traffic control measures. On January 23, 2020, Wuhan announced a policy to shut down the city, while subway, bus and other transportation infrastructure were suspended. Limited transport capacity gives priority to medical supplies and necessities. Even with all of China’s efforts, the supply capacity is still clearly inadequate, not to mention the fact that other non-essential goods can hardly be delivered in time. According to the data of 33 main e-commerce websites in Wuhan, the intra-city delivery time was as high as one to three days (Bendibao, 2020). As the situation worsened, Wuhan imposed stricter community lockdown policies on February 11,
2020. Each community centralized the distribution of daily necessities to the residents. By mid-March, the epidemic had eased, and the community lockdown was lifted. The city’s public transport system was gradually returning to work. On April 8, 2020, Wuhan announced the lifting of the lockdown policy.

Since the official data has not been made public, this study investigated residents’ daily needs and deprivation cost of 416 families in CAA during the epidemic period. The results of the survey are shown in Appendix. Combined with the survey data samples, it was assumed that the packages were all cubes with a side length of 30 cm, which served as the basis for modeling.

Fig. 3 shows the per capita freight volume ($PV$) of the sample from January 23, 2020 to April 8, 2020, about 1–2.5 parcels, which is obtained based on the survey and reasonable prediction of Wuhan Statistics Bureau data. During the epidemic, the parcels were mainly essential items for residents’ daily life. After 23 January, due to the policy of closing down the city, the number of times residents went out for shopping decreased, and $PV$ decreased significantly. Until 11 February, after the community closure, a large number of relief supplies rushed to Wuhan, resulting in a gradual increase in $PV$. As the lockdown gradually lifted, workers returned to work, further boosting the city’s overall freight demand. According to data released by HuoLaLa (2020), a large urban distribution company in China, before Wuhan’s closure, the city shipped 50% of its usual amount of consumer goods.

To simplify the model, it is assumed that after 11 February, $PV$ increases linearly and reaches 2.5 parcels per person per day on 8 April. In the case of non-epidemic, during this period, considering that many logistics enterprises are closed during the traditional Chinese Spring Festival, it is assumed that $PV$ is 1.25 parcels per person per day from 23 January to 31 January, and increases to five parcels per person per day after the festival.

As described above, the M-ULS network can connect the logistics park outside the CAA and the main demand points inside the area. The blue area in Fig. 4 shows the geographic information of CAA. A total of eight subway lines (208 km long) and 131 stations are within CAA, which can provide high-density subway network to effectively promote the implementation of M-ULS. At the same time, almost all communities and logistics demand points such as major hospitals, business and administrative areas are adjacent to subway stations and are effectively covered by the M-ULS network. The network can meet the transportation needs of forward and reverse logistics, including the reverse recovery of medical waste.

In addition to mitigating the negative externalities of city logistics, M-ULS also have significant advantages over traditional surface transport in responding to urban emergencies such as COVID-19. Highly intelligent transportation system can greatly reduce the manpower demand in every link of urban distribution, including the whole process from distribution center to terminal delivery. In this way, the necessary
disinfection and quarantine procedures are reduced, and the delivery speed is improved. More importantly, the risk of transmission of the virus through contact with cargo personnel was significantly reduced.

3.2. System boundary

In order to analyze the challenges faced by city logistics during the outbreaks of the epidemic, the proposed model mainly included three factors: truck transportation process, M-ULS operation process, and the performance of city logistics.

For the truck and M-ULS transportation process, the model takes into account basic parameters related to transportation, such as freight demand, freight capacity and freight volume. Meanwhile, the attractiveness of M-ULS (AM) is a key element variable that determines M-ULS’s operational requirements and determines its market share. Utilization rate is also an important parameter to indicate the running state of M-ULS.

As for the performance of city logistics, this paper selected five representative parameters, namely, demand-fill rate (DR), unit delivery time (UDT), total transportation cost (TTC), total deprivation cost (TDC) and total number of susceptible people (TNP), to evaluate the effectiveness, efficiency and risk of city logistics under the epidemic. Additionally, utilization rate of M-ULS (UM) is selected to represent the operation condition of M-ULS.

3.3. Causal loop diagram (CLD)

CLD was built using Vensim 7.2 software based on the determined parameters. The CLD is composed of three modules: M-ULS operation subsystem, truck transportation operation subsystem and city logistics performance subsystem, as shown in Fig. 5. Four feedback loops are formed to represent the causality relationships or feedback mechanisms between the main variables. The variables are linked by causal chains that represent positive and negative effects. The plus sign indicates that the variables change in the same direction, and the minus sign indicates the opposite direction (Emberger and Paffenhöller, 2020).

Reinforcing loop R1 depicts the impacts of scale effect on M-ULS operation. As the freight volume in the M-ULS increases, transportation cost will gradually decrease, which will promote the market to place more orders to M-ULS.

Balancing loops B1 and B2 reflect the relationship between the performance of truck transportation and M-ULS operation. The application of M-ULS will reduce the risk of epidemic transmission caused by contact during transportation. Furthermore, the low efficiency and timeliness of truck transportation, especially during the epidemic period, further promotes the implementation of M-ULS and the expansion of its orders.

Balancing loops B3 contains a set of negative loops, indicating that the freight capacity of the M-ULS will limit its freight volume. When freight demand exceeds the maximum capacity of M-ULS, delivery delays will limit the AM and then decline the freight orders of M-ULS.

It is worth noting that, like other green logistics technologies, the AM is strongly influenced by local government policies, as is trucking. The government can regulate and supervise the freight market by providing subsidies and guiding policies.

3.4. Simulation model formulation

The stock-flow diagram was established by integrating and expanding the key feedback loops (Fontoura et al., 2019). The three subsystems were described separately due to the complexity of the overall SD model hierarchy. Table 1 lists the main variables and their reference sources.

3.4.1. Truck transportation subsystem

This subsystem depicts the daily operation of ground truck transportation which is affected by the supply-demand of freight market, as shown in Fig. 6.

As the key elements of the supply side, trucking freight capacity (TC) is directly affected by the number of available trucks (NT), daily truck trips (DT) and freight handling capacity per truck trip (FT), as shown in Eq. (1).

\[ TC = NT \times DT \times FT \] (1)

The values of NT, under normal conditions and epidemic outbreaks, are shown in Table 2, respectively, where the intervals between key points are supposed to be filled by linear interpolation. The data of NT is calculated by statistical data of Wuhan Municipal Bureau Statistic (2018). It is assumed that 90% of the trucks in the city participate in daily freight. NT was greatly affected by the Spring Festival holiday and the city closure policy. In a normal year, the NT during the Spring Festival is about one-eighth of the total (The Paper, 2020b). In this year’s COVID-19 outbreak, the initial value of NT was slightly higher than that of normal years, due to government investment and the participation of volunteers (The State Council Information Office of PRC, 2020). According to the report of HuoLaLa (2020), before the lifting city blockade of Wuhan, NT was about 31% of the total. Eq. (2) describes NT, where WITH LOOKUP means the variables can be described through a table function of the independent variables.

\[ NT = WITHLOOKUP \times \text{TIME}, \ (\text{TIME} = \text{TIME}_0, \text{TIME}_m) \] (2)

On the demand side, the freight demand of trucking (FDT) and the
actual freight volume of trucking (FVT) are determined by both the intraday orders and the unmet orders of the previous days, as shown in Eqs. (3) and (4). The model also introduced a time sequence for delivery, which depends on the priority of goods. Priority is given to orders that have not been delivered before. The earlier the order is placed, the higher its priority is. In addition, the distribution of medical waste should be given the highest priority under the epidemic situation.

\[
FDT = NOT + BOO + BOT + BOTD + CW
\]  
\[
FVT = IF THEN ELSE (UOO > 0, TC, NOT + BOO + BOT + BOTD + CW)
\]

The unit delivery time of trucking (UDTT) is the average delivery time of all orders completed on the same day. Due to possible shipping delays, UDTT is determined by truck transportation order structure and the actual delivery time of each order. The delivery time of orders in the model was set as one to four days. For example, if the new order can be delivered on time, the delivery time will be one day. If there is an undelivered order on the previous day, the delivery time of that order is increased by one day.

\[FDT = NOT + BOO + BOT + BOTD + CW\]  
\[FVT = IF THEN ELSE (UOO > 0, TC, NOT + BOO + BOT + BOTD + CW)\]

3.4.2. M-ULS operation subsystem

Fig. 7 shows the M-ULS operation process and its relationship to the customer’s preference for mode of transportation.

Freight capacity of M-ULS (FCM) depends on its system capacity. FCM is proportional to the freight handling capacity of the M-ULS station (FHM) and the number of planned stations (MSN), as shown in Eq. (5). According to Dong et al. (2018) and Hu et al. (2020), the transformation of about 40% stations in the subway network into freight stations can effectively cover the whole area. Parameters are set as shown in Table 3. Since passenger traffic is suspended during the epidemic outbreak and M-ULS will be fully serviced for freight, allowing FHM to be set at 1.5 times its normal level. Then, with the resumption of urban traffic, the FHM will return to the normal level.

\[FCM = FHM \times MSN\]

Delivery time and transportation cost are the main factors influencing the adoption of M-ULS (Hu et al., 2020b). More orders will always prefer the cheaper and faster mode of transportation. Thus, cost index (CI) and time index (TI), were introduced to depict AM, as shown in Eq. (6). TI depends on the ratio of unit delivery time between trucking and M-ULS. CI is shown in Eq. (7), which is not only determined by the unit transportation cost of two transportation modes, but also affected by the government subsidies represented as subsidy index (SI). According to AM and FCM, the daily new orders of M-ULS (NM) are shown in Eq. (8). In addition, the M-ULS’s response time was also considered in the model.

\[AM = DELAY (CI \times EI, 1, 0)\]
\[CI = \frac{UTCT}{(UTCM \times SI)}\]
\[NM = AM \times FCM\]
Table 1
Main variables in the model.

| Variable                                         | Acronym | Source                          |
|-------------------------------------------------|---------|---------------------------------|
| Attractiveness of M-ULS                         | AM      | Hu et al. (2020b)               |
| Backlogged orders of one day ago                | BOO     | Hu et al. (2020a)               |
| Backlogged orders of two days ago               | BOT     | Hu et al. (2020a)               |
| Backlogged orders of three days ago             | BOTD    | Hu et al. (2020a)               |
| Cost index                                      | CI      | Hu et al. (2020b)               |
| Collected medical waste                         | CW      | Yu et al. (2020)                |
| Daily truck trips                               | DT      | Dong et al. (2019)              |
| Demand-fill rate                                | DR      | Singh et al. (2020)             |
| Exposure people during transportation            | ET      | Yu et al. (2020)                |
| Freight capacity of M-ULS                       | FCM     | Hu et al. (2020b)               |
| Freight demand of M-ULS                         | FDM     | Dong et al. (2019)              |
| Freight demand of M-ULS                         | FDM     | Hu et al. (2020b)               |
| Freight handling capacity of the M-ULS station   | FTM     | Hu et al. (2020b)               |
| Freight handling capacity per truck trip        | FTC     | Dong et al. (2019)              |
| Freight volume of M-ULS                         | FVM     | Hu et al. (2020b)               |
| Freight volume of trucking                      | FVT     | Dong et al. (2019)              |
| Number of planned stations                      | MSN     | Hu et al. (2020b)               |
| New orders of M-ULS                             | NM      | Hu et al. (2020b)               |
| New orders of trucking                          | NOT     | Hu et al. (2020a)               |
| Number of susceptible people                    | NP      | Yu et al. (2020)                |
| Number of available trucks                      | NT      | Dong et al. (2019)              |
| Probability of human-to-human transmission risk | PS      | Yu et al. (2020)                |
| Per capita freight volume                       | PV      | Dong et al. (2019)              |
| Subsidy index                                   | SI      | Hu et al. (2020b)               |
| Trucking freight capacity                       | TC      | Dong et al. (2019)              |
| Total deprivation cost                          | TDC     | Holguín-Veras et al. (2013)     |
| Time index                                      | TI      | Hu et al. (2020b)               |
| Total number of susceptible people              | TNP     | Yu et al. (2020)                |
| Total transportation cost                       | TTC     | Hu et al. (2020b)               |
| Unit delivery time                              | UDT     | Dasaklis et al. (2012)          |
| Unit deprivation cost                           | UDC     | Holguín-Veras et al. (2013)     |
| Unit delivery time of M-ULS                     | UDTM    | Hu et al. (2020b)               |
| Unit delivery time of trucking                  | UDTT    | Dasaklis et al. (2012)          |
| Utilization rate of M-ULS                       | UM      | Hu et al. (2020b)               |
| Unfulfilled orders of one day ago                | UOO     | Hu et al. (2020a)               |
| Unit transportation cost of M-ULS                | UTM     | Hu et al. (2020b)               |
| Unit transportation cost of trucking             | UTT     | Hu et al. (2020b)               |

previously uncompleted orders. The freight volume of M-ULS (FVM) is the amount of cargo it handles on that day. In addition, in order to reduce the risk of virus transmission and secondary infection, it was assumed that medical waste is transported by M-ULS in the presence of M-ULS.

UM, which is influenced by the FVM and FCM, was then introduced to evaluate the performance of M-ULS operation, as shown in Eq. (9).

\[ UM = \frac{FVM}{FCM} \quad (9) \]

3.4.3. City logistics performance subsystem

Fig. 8 describes the relationship between the city logistics and the freight operation. The performance of city logistics was measured by five variables, including TTC, DR, UDT, TDC and TNP.

DR and UDT were adopted to jointly reflect the city logistics effectiveness. DR reflects the order fulfillment every day. UDT describes the average delivery time of orders within a day. As shown in Eq. (10) and Eq. (11).

\[ DR = \frac{FVT + FVM}{FDT + FDM} \quad (10) \]

\[ UDT = \frac{UDTM \times FVT + UDM \times FVM}{FVT + FVM} \quad (11) \]

TTC and TDC were used to describe city logistics efficiency. TTC represents the cumulative transportation cost over the simulation period, depending on the respective freight volume of the truck and M-ULS as well as the unit transportation cost. The unit transportation cost of M-ULS (UTCM) is inversely proportional to FVM, which means that UTCM decreases with the increase of FVM, as shown in Eq. (12).

\[ UTCM = \frac{1}{FVT + FVM} \quad (12) \]

TDC represents the accumulated deprivation cost caused by delivery delay in the transportation of truck and M-ULS during the simulation.

Table 2
Variable setting of Number of available trucks.

| Scenarios          | 23 Jan | 31 Jan | 11 Feb | 25 Feb | 8 Apr |
|--------------------|--------|--------|--------|--------|-------|
| Normal years       | 6000   | 6000   | –      | 48,000 | 48,000 |
| Epidemic outbreaks | 8000   | –      | 8000   | –      | 14,900 |

Fig. 6. Truck transportation subsystem. (2-column).
The deprivation cost is calculated on a daily basis and the unit deprivation cost (UDC) depends on the probability of human-to-human transmission risk (PHTR) and exposure people during transportation (ET), as shown in Eq. (13). TNP is the accumulated NP during the simulation period.

\[ NP = PS \times ET \]  

(13)

### 3.5. Model validation

Validation test of SD model, such as model structure and behavioral tests, is necessary before simulation (Sterman, 2000). First, the model structure, such as stock and flows variables, and equations, was tested using direct inspection and comparing with the knowledge about the structure of the generic logistics operation. For dimensional consistency, the Vensim 7.2 software build-in tool was used to check the model units.

The comparison between the simulated data and historical data of the two variables is shown in Fig. 9. Both sets of data show a good fit for data from 12 February, with errors of just 1.5% and 5.4%, respectively. The poor fit of the initial data is due to the fact that on 12 February, Wuhan updated the diagnostic methods, re-examined the suspected cases, and modified the previous diagnosis results, resulting in a large difference between the number of reported cases and the actual cases. Therefore, in addition to data fluctuations caused by emergencies, the simulation results conform to the common SD model testing standard (Emberger and Pfaffenbichler, 2020), indicating the good validity of the model.

## 4. Results and discussion

### 4.1. Scenarios setting

Five different simulation scenarios were designed by combining three city logistics policies that can effectively curb the epidemic: the implementation strategy of M-ULS, the policy of city closure and the government’s subsidy strategy, as shown in Table 5. Six indicators, namely DR, UDT, TTC, TDC, TNP and UM, were used to analyze the city logistics performance under different policy sets. The simulated time is consistent with the period of city closure in Wuhan, from January 23, 2020 to April 8, 2020.

In S5, the role of government subsidies in promoting the implementation of M-ULS and improving the overall city logistics performance is discussed by changing the value of SI. Where SI under S5 is assumed to be 0.85 and 1 in other scenarios.

### 4.2. Benefit analysis of M-ULS (no COVID-19 scenario)

In Fig. 10, the city logistics performance under S1 and S2 is compared. There is no COVID-19 epidemic in either scenario, or the policy of city closure is also not implemented. S2 is superior to S1 in all aspects, indicating that M-ULS significantly improves city logistics. Of course, this has been proved in Dong et al. (2019) and Hu et al. (2020). This paper only used the data of Wuhan to verify again that M-ULS is an effective supplement to the existing city logistics.

Fig. 10(a-b) shows that, compared to S1, the implementation of M-ULS contributes to an increase in urban freight capacity, resulting in an increase in DR and a decrease in UDT. In Fig. 10 (c), the TDC of S2 reaches $594.8 million, which is 61.5% less than that of S1. However, the TDC difference between the two is not significant, as shown in Fig. 10 (d). This is due to the limited capacity of M-ULS under mixed passenger and cargo transportation. Even full load operation can only meet 13.7% of the city’s total freight demand. In spite of this, M-ULS still shows huge external benefits based on the comparison results of S1 and S2. Fig. 10 (e) shows the simulation results of UM, showing an obvious upward trend and the growth rate of UM increases significantly. The simulation

| Scenarios | 23 Jan | 28 Mar | 8 Apr |
|-----------|--------|--------|-------|
| Normal years | 80,000 parcels/day | – | 80,000 parcels/day |
| Epidemic outbreaks | 120,000 parcels/day | 120,000 parcels/day | 80,000 parcels/day |

By comparing the simulated data with the historical data, it can be seen that the model structure and the behavior of the model are well validated.
results show that M-ULS still has great market competitiveness. Because its transport scale effect reduces unit transport cost, although the advantage in delivery time will diminish with its widespread application.

4.3. The influences of city closure policy on city logistics (no M-ULS scenario)

The comparison between S1 and S3 can reflect the impact of city closure policy on city logistics, as shown in Fig. 11. There is no implementation of M-ULS in either scenario. Fig. 11 (a) shows that the traffic control measures caused by the epidemic have greatly reduced DR. During the closure of the city, the demand for freight decreased significantly, but the huge gap in freight capacity caused by the shutdown and other factors led to the continuous decline of DR, which dropped to 36.6% on 3 February. With the introduction of the government freight incentive measures and many volunteers to participate, DR has been greatly enhanced. Between 23 February and 1 March, all the orders of the same day have been processed in time. After the closure lifted of communities and the resumption of work, the demand for freight continued to grow, but the existing logistics model was still unable to meet the demand. DR continued to decrease until the city was unsealed only 26.4%. As a result, delivery delays were the norm during outbreaks, with UDT as high as 3.4 days on 8 April as shown in Fig. 11 (b).

Fig. 11 (c) reflects the impacts of city closure on TDC. From 23 January to 12 March, the “S” shaped TDC curve indicates that the parcels can be delivered timely as the city’s freight capacity increases. But then the existing trucking system hit a bottleneck. TDC shows a significant upward trend, reaching $2.6 billion during the city closure, 73.3% higher than normal.

Fig. 11 (d) depicts TNP during the city closure. The spread of the epidemic showed a decreasing trend with the continuous closure of the city (Wu et al., 2020), which was also reflected in the TNP curve. Although freight demand gradually increased, the TNP growth trend gradually flat. Therefore, controlling the number of people involved in freight transportation during the initial phase of the epidemic is a decisive factor in reducing transport risks.

In general, compared with the normal situation, during the duration of the epidemic, the contradiction between the growth of freight

| Delivery time | 1 day | 2 days | 3 days | 4 days |
|---------------|-------|--------|--------|--------|
| Unit deprivation cost | $0    | $4.9   | $11.3  | $28.3  |

Table 4
Variable setting of Unit deprivation cost based on the delivery time.
demand and the limited freight capacity of cities is more prominent. The traditional city logistics distribution mode, which relies on the ground road and human driving, is seriously inadequate in dealing with emergencies. Particularly, increasing the number of lorries and drivers to eke out more capacity is an obvious last resort in an epidemic. Although it can reduce the deprivation cost caused by delivery delay, it will increase \( TNP \) greatly. Therefore, the COVID-19 outbreak has exposed severe urban distribution bottlenecks, and M-ULS is an effective complement to the labor-intensive logistics distribution method.

4.4. The influences of M-ULS implementation on city logistics under epidemic outbreaks

Fig. 12 reflects the improvement of M-ULS implementation on city logistics performance by comparing the city closure scenarios of S3 and S4. Fig. 12 (a) shows that the trend of \( DR \) appears in a “U” shape in S4. Due to the low market share of M-ULS, \( DR \) shows a downward trend in the initial stage of city closure, which dropped to 64.6% on 26 January. However, with the increase in capacity, M-ULS was highly attractive in transportation cost and delivery times, and \( DR \) subsequently rises sharply. In addition, Fig. 12 (b) also shows that the application of M-ULS is an effective supplement to truck transportation. \( UDT \) is going down fast and remains around one day. However, this trend will eventually attract orders beyond the M-ULS capacity limit, leading to delivery delays where the \( UDT \) curve vibrates slightly.

Fig. 12 (c) illustrates that \( TDC \) of S4 reaches $107.6 million during
city closure, about 95.9% lower than that of S3. Various factors lead to this significant decrease. The large-scale application of M-ULS can achieve faster urban delivery and a higher demand-fill rate. And traffic control policies will force more goods to be transported via M-ULS. Like the change of TDC, the TTC results are shown in Fig. 12 (d). The TTC reached $125.1 million during the city closure, down about 23.3% from S3.

Fig. 12 (e) reflects the role of M-ULS in controlling the risk of infection transmission during transportation. The non-contact transportation features of M-ULS reduced TNP to 228.9 thousand people, about 48.8% less than that of S3. The TNP curve quickly becomes stable after M-ULS is widely adopted, which reflected this advantage. In contrast, TNP grew rapidly when M-ULS market share was low, that is, at the early stage of city closure.

To sum up, compared with ground truck transportation, the huge comprehensive benefits reflect the flexibility of M-ULS in dealing with traditional problems of city logistics and emergency situations. However, the tension between the limited capacity of M-ULS and the growing demand for freight will also become apparent. Hence, effective means are needed to optimize the operation of M-ULS and the stable expansion of the network, so as to continuously improve the performance of city logistics.

4.5. The influences of government subsidies on M-ULS implementation

Fig. 13 verifies the effectiveness of the government subsidy strategy by comparing S4 and S5. Government subsidies can effectively accelerate the application of M-ULS, as shown in Fig. 13 (a). Under S5, M-ULS runs at full capacity in just six days, two days earlier than S4. Moreover, due to its huge market competitiveness, M-ULS has always maintained a high UM after being widely used.

Fig. 13 (b–f) reflects the benefits of earlier implementation of M-ULS. Under S5, the improvement of DR and UDT is more obvious. Meanwhile, TDC and TNP decline to $57.9 million and 187 thousand people, respectively, about 46.2% and 18.3% lower than S4. However, the same freight capacity of M-ULS makes no significant difference in TTC between the two scenarios. Additionally, TDC increases slightly, indicating that the limited capacity of M-ULS set in this paper still cannot meet the increasing freight demand.

Therefore, even a tiny increase in M-ULS market share can bring enormous benefits. Especially in the early stage of city closure, the risk of virus transmission is high, and the introduction of M-ULS should be accelerated. Clearly, government subsidies are extremely effective. But fiscal measures alone may not be enough. Other incentives, such as mandatory quotas for users to use M-ULS, can accelerate the expansion of M-ULS. In city closure scenarios, the performance of M-ULS is more prominent during transportation disruption. In summary, the comprehensive advantages of M-ULS lead to its rapid adoption.

4.6. Policy implication

According to the simulation results, a portfolio of possible incentives
was designed for different stages of city closure to promote the application of M-ULS and thus to solve the worsening city logistics. Incentives are depicted in Fig. 14.

- In the ex-ante, or non-emergency period of city closure, incentives should focus on M-ULS related infrastructure construction and social acceptance advocacy. Similar to urban subways, M-ULS have obvious public infrastructure attributes, and local government should provide adequate investment in their network construction. Of course, Public-Private Partnership (PPP) is an effective way to reduce financial expenditure and ease M-ULS high construction investment. Meanwhile, extensive publicity and encouragement of use contribute to the acceptance of M-ULS. In addition, with some policy measures, such as congestion pricing, truck parking fees, and carbon tax, internalizing the external cost of freight transportation will accelerate the market penetration of M-ULS and drive users to shift to the M-ULS.

- In the initial stage of city closure, the local government should strengthen policy and financial support to accelerate the promotion of M-ULS to obtain more overall benefits. As for the financial support, tax breaks and freight subsidies for users can be implemented to expand market share, and the operating cost of M-ULS is subsidized.
through fiscal expenditures. In terms of freight management, the government should collect the freight data, such as freight volume, good types and freight flow information, to coordinate the overground and underground freight and give full play to the advantages of M-ULS. For instance, items with high immediacy should be transported preferentially by M-ULS. Meanwhile, for the high-hazard items such as medical waste, the government can require hospitals and other institutions to use M-ULS for transportation. At the height of the epidemic, temporary freight quota policies should also be imposed to enforce the adoption of M-ULS. Moreover, the government should actively guide the transformation of urban freight mode, vigorously promote contactless distribution, and further promote the application of M-ULS and other intelligent unmanned logistics.

- In the late stage of city closure, the government should integrate the ground freight system and M-ULS to achieve the maximum logistics benefits. Based on the huge benefits of M-ULS during the initial stage of city closure, the government can take proactive measures to promote this highly efficient transportation mode to its potential users. Moreover, with the increase in freight volume, the operator of M-ULS should fully integrate the resources of the subway system to improve the freight capacity of M-ULS. For instance, readjusts subway schedules to optimize the system to free up more underutilized capacity to improve the logistics efficiency of M-ULS. Especially in the emergency state, passenger transport function is extremely surplus and even can be temporarily closed, the transport of emergency supplies can be scheduled in order of priority. In addition, M-ULS operator should establish the emergency response system and standardized transportation process to optimize the system operation.

Fig. 14. Incentives for the application of M-ULS. (2-column).
After lifting the city closure, the urban operation gradually returns to normal. Meanwhile, it should return to how to make full use of underground transportation to alleviate the negative externality of city logistics, which needs to provide a series of incentives for the long-term network development of M-ULS. For example, maintain continuous investment and incentive policies to promote network expansion. The network of M-ULS can be expanded on the original subway network, and new capillary network can also be planned to expand the coverage of the system. Meanwhile, the government can invest in more pilot projects to show the feasibility of M-ULS through improved visibility. Additionally, the operation optimization and technological innovation of M-ULS should also be continued. The government can also grant awards for R&D of M-ULS. Of course, the existing promotion initiatives of green logistics and sustainable logistics will also play a positive role in the application of M-ULS.

The government needs to play the role of regulator in addition to being a major investor under both epidemic and normal situation. However, under normal situation, the development and the operation of M-ULS are greatly affected by market laws. Thus, the incentives should be more fully in line with the mechanism of freight market operation. The corresponding incentives are also shown in Fig. 14.

In the initial implementation period, the market acceptance and market share of M-ULS are relatively low. The government should regulate the freight market to avoid vicious competition and prevent the phenomenon of “bad money drives out good”. In addition, clarifying the carbon reductions path for urban freight transportation and the relevant time points will also drive users to adopt more environmentally friendly M-ULS service. As for the M-ULS operation, the freight rate reduction strategy should be taken to accelerate the market penetration process. Of course, similar to the incentives under epidemic situation, the development of M-ULS is inseparable from the strong marketing and sustained financial support.

With the enhancement of the market acceptance, the freight demand will see a substantial increase. Users should be encouraged to participate in the M-ULS operation process, so as to further improve the market acceptance and the service quality of M-ULS. The government should also include the M-ULS in the planning of city logistics and perfect the carbon cap-and-trade mechanism of freight market, thus facilitating the transition of traditional trucking to green logistics such as M-ULS. In the operation process of M-ULS, the scale effect of freight transport needs to be fully utilized to form the cost advantages.

5. Conclusions

The COVID-19 outbreak has intensified the demand for innovation in city logistics, especially contactless smart logistics. The comprehensive advantages of M-ULS are paid more attention by city managers. However, the performance and social acceptance of M-ULS have not been quantified effectively. During the epidemic, the uncertainty of the urban freight market makes the market evolution based on M-ULS more complex. Hence, this study explored both the external benefits and market penetration process of M-ULS during the city closure of Wuhan, China. According to the actual transportation policies and the dynamic change of the freight market, the SD model of city logistics based on M-ULS was established. DR, UDT, TTC, TDC and TNP were used to evaluate the city logistics performance, and the operating conditions of M-ULS were explored according to the simulation results of UM. Finally, a multi-stage incentive policy framework was proposed to promote the application of M-ULS.

The factors related to the adoption of M-ULS play different roles in its market penetration. In the initial stage, the high efficiency of M-ULS is the main driving force. With the increase of market share, UDT declined sharply, and M-ULS’ market competitiveness turned to the cost advantage brought by its freight scale effect. Financial support from the government can compensate for the high cost of operating ULS, thus attracting more users. However, limited freight capacity still fails to meet the growing demand for freight, so operators should continue to carry out technological and management optimization innovation.

During the COVID-19, M-ULS occupies the city logistics market more quickly. The overall flexibility of the M-ULS is particularly prominent in the event of transport disruptions. This flexibility is not only reflected in the accessibility of transportation, but also can make a trade-off among the effectiveness, efficiency and risk of city logistics. In the case of this paper, the M-ULS capacity parameter set still cannot fully meet the needs of the city, but under full load operation, UDT has been reduced to one day, and TDC, TNP and TTC have been reduced by 95.9%, 48.8% and 23.3%, respectively.

The infrastructure nature of M-ULS determines that its main source of investment should be the local governments, regardless of the financing mode. The high construction investment and operation cost make it need dynamic policy support based on market changes in the development process, including franchise operation, mandatory resource allocation and extensive guidance. In the state of emergency, the policy should focus on adjusting and controlling the priority of material transportation and the market share of such contactless intelligent logistics, so as to meet the needs of urban relief and the basic living guarantee of residents. Under the normal situation, however, the development of M-ULS is largely determined by the law of market economy, and thus the government should also play the role of coordinating the freight market.

Several limitations inevitably appear in this study and represent valuable directions for future research. First, this paper focused on two typical types of users’ preference related factors, namely transportation cost and delivery time. It would be interesting to further explore how other factors, such as service reliability and infrastructure compatibility, may influence the application of M-ULS. Second, the deprivation cost of the model was not subdivided and analyzed according to the different types of goods. Third, based on the view in this paper, further using the operational research model to analyze the comprehensive benefits for specific M-ULS network form will be an important direction of follow-up research. Fourth, the emergencies such as tracks or freight vehicles damage will affect the M-ULS operation, and thus how to quantitatively analyze the resulting impacts and establish corresponding management measures are worthy of in-depth study. Last but not least, the epidemic outbreaks have greatly affected the operation of M-ULS and trucking, and thus the dynamic analysis of the transportation-related emissions is also the focus of the further research.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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