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RESEARCH ARTICLE

Research on the Design and Sustainable Evaluation of Metro-Based Underground Logistics Systems

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ABSTRACT Along with the development of underground space and the increasing maturity of automation technology, a new type of transport and supply system called "Underground Logistics System (ULS)" is gradually gaining attention in various countries as an effective means of solving the problem of urban traffic congestion. However, the high cost and risk of underground construction are the main factors that have led to ULS remaining in the theoretical stage for the time being. Therefore, the paper aims to design a solution for implementing a metro-based underground logistics system (M-ULS). Firstly, the paper uses the K-mean clustering algorithm and genetic algorithm for path planning of conventional ground transportation and M-ULS. Secondly, the article is a retrofitting design for a site that combines the metro with an underground logistics system and simulates the underground logistics nodes with the help of AnyLogic simulation software. Finally, the paper explores the economic and environmental value of M-ULS in terms of carbon emissions, time costs, fuel costs, and environmental pollution costs. The research provides a solution to alleviate urban traffic congestion, reduce environmental pollution and promote sustainable urban development.

INDEX TERMS Metro-based underground logistics system, K-mean clustering algorithm, genetic algorithm, AnyLogic simulation, sustainable urban development.

I. INTRODUCTION

Since the beginning of the 1990s, the global economy has developed rapidly. In particular, the rapid expansion of e-commerce and express business has led to a dramatic increase in logistics demand market trade with each passing day. The Organization for Economic Co-operation and Development (OECD) has carried out a project to forecast global freight demand. Its results show that global surface freight ton kilometres will double from 2015 to 2030, especially in Asia, where they will increase 3.2 times [1], [2]. In urban logistics, road transport has become the main mode of urban logistics to achieve convenience and speed. Along with the proliferation of logistics vehicles, increased traffic pressure and reduced transport efficiency have become important factors hindering urban development. According to the Annual report of Beijing's traffic development in 2019, the annual economic loss due to traffic congestion in the city is hundreds of billions of dollars.

One effective way to tackle urban traffic congestion is to ease the burden of transporting cargo [3], [4]. Because of the shortcomings of road transport in terms of small transport areas, high transport costs and environmental pollution, optimizing the road transport capacity of urban logistics has become the key to improving traffic congestion in cities. Expansion of the traditional road network capacity is difficult due to the city's very tight urban sites. It is theoretically and realistically infeasible to meet the growing demand for transport solely through additional transport facilities when there are economic, technological, environmental and spatial

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constraints [5]. As a result, many scholars have turned their research attention to the development of underground space. Along with the continuous development of transport technology and theory, underground logistics system is gradually gaining attention in many countries. The underground logistics system is a transport and supply system that automates transport within and between cities through enclosed spaces such as underground pipes or tunnels [6]. The ULS unifies different types of logistics such as industrial parks, extra-provincial transport of living materials, express delivery and medical materials in a single route to each demand point. It can make full use of urban underground space, relieve the pressure of above-ground traffic and reduce urban environmental pollution and noise hazards. Compared to other traditional freight systems, underground logistics freight systems can independently separate cargo and passenger transportation, independent of weather and other economic conditions, and are an effective way to build sustainable urban logistics development [7].

Studies of underground space have shown that the costs and risks of a new underground logistics system are significant. This is why many scholars have put forward the idea of "subways instead of underground logistics", which can significantly reduce construction and operating costs by modifying existing underground lines and using the surplus capacity of the underground for cargo transport [8].

Therefore, this paper aims to design a solution for the implementation of a metro-based underground logistics system. The city of Chongqing, China, is used as the subject of the study. By comparing the carbon emissions, time costs, fuel costs and environmental pollution costs of traditional surface transport and M-ULS transport, this paper studies the economic value, environmental protection value and sustainable development value that M-ULS has, and explores the feasibility and effectiveness of building M-ULS. This study provides a solution to alleviate urban traffic congestion, reduce environmental pollution and promote sustainable urban development.

With carbon emissions and traffic congestion becoming increasingly important, research into underground logistics is also growing as an effective way of addressing these issues. Scholars have discussed in various details, from the realization of underground logistics systems to path planning, evaluation methods and development trends. However, existing research has mainly focused on theoretical analysis and less on how to construct underground logistics systems in concrete terms.

Underground logistics has been developed for nearly half a century, marked by the concept of "solid freight pipelines" proposed by Zandi [9]. Various countries around the world have carried out different degrees of practice, such as Japan's Dual Mode Truck system, Switzerland's Cargo Sous Terrain system, the US Hyperloop vacuum tube freight system, Germany's Cargo-Cap system, etc [10]. ULS was first formally proposed in 2007 as a solution to traffic congestion in China's mega cities [11]. With the development of economy and technology, the concept of underground logistics has been gradually refined and numerous scholars have started to study feasible ways of implementing ULS. For example, Heijden studied the establishment of an underground logistics corridor between Schiphol Airport and the Amsterdam Flower Market, analyzing the operational characteristics, costs and efficiency of different underground logistics networks [12].

Considering the technical requirements and cost requirements of actually building an underground logistics system, more and more scholars are inclined to study ways of building underground logistics based on existing transport. Rijsenbrij's creative approach to combining freight transport and urban underground technology [13]. Subsequent studies have explored ways to combine underground logistics with integrated pipeline corridors [14], rail transit and underground roads [15]. A new intelligent underground logistics model based on big data has also been proposed [16]. Of these, M-ULS is considered to be one of the more feasible approaches. Some studies have constructed M-ULS network traffic configuration models with environmental benefit expectations for underground freight [17]. One study developed a ULS network planning method based on a metro system [18]. A framework containing 37 key technologies required for M-ULS development has also been evaluated [19]. When looking specifically at how ULS can be combined with the metro, some studies quantified three possible ways of M-ULS. They concluded that due to the limited capacity of the metro, the only way to fundamentally solve the logistics transport problem is to adopt separate transport lines or separate networks for the ULS [20]. Some studies have also explored the combined passenger and freight metro logistics transport mode and concluded that the passenger and freight common line has certain advantages as a transitional mode, but cannot replace the underground logistics system due to the limitations of metro logistics [21].

The selection of logistics nodes and logistics paths is a key element of research in all forms of ULS implementation. The selection of suitable locations for freight transfer centres in underground logistics systems is a common approach using a weighted ensemble coverage problem model and reasonable forecasts of freight volume data for major cities [22]. Also, the theory of uncertainty maps and dynamic programming [23] and fuzzy clustering methods [24] are commonly used in planning problems for ULS. In addition to this, many studies have continued to improve the excellence of ULS planning from an algorithmic point of view, such as genetic algorithms [25], greedy genetic algorithms [26], hybrid immune genetic algorithms [27], simulated annealing algorithms [28], bat algorithms [29], and plant growth algorithms [30]. Following the design of the planning of the metro system, some studies have simulated the underground logistics system using simulation software, such as AnyLogic [31], Flexsim [21], Automad [32], etc.

Following a theoretical discussion, numerous studies have assessed the benefits of building ULS in terms of its feasibility and effectiveness. Some scholars have proposed some strategies and opinions for the development of ULS using models based on macro-environmental and situational analysis (PEST-SWOT) [33]. From other perspectives, some scholars have studied the economic advantages of electrically powered underground logistics over conventional transport [34]. Some scholars have also used a system dynamics approach to analyze the quantitative relationship between the implementation strategies of ULS and the sustainability of urban transport and logistics [35]. In specific studies, time costs [24], [36], emissions and congestion costs [24], additional fuel consumption costs [36], construction costs, and usage costs [16] are the aspects that have been more frequently used to evaluate the effectiveness of ULS.

The studies that have been carried out are mainly from a qualitative analysis point of view, while there is still room for improvement in terms of the design of the transformation of underground spaces and the comparison of conventional transport with ULS. And scholars have studied less about the synergistic transport f ways of ULS and the metro. To practically explore the feasibility of implementing M-ULS in China, this paper takes the city of Chongqing, China, as a case study. Firstly, to minimize the total path, the K-mean clustering algorithm and genetic algorithm were used for path planning of conventional surface transport and M-ULS. Secondly, the original metro station was modified and a design solution for the transformation into an underground logistics node was proposed and simulated in AnyLogic simulation software. Finally, the M-ULS is evaluated in terms of four aspects: carbon emissions, time cost, fuel cost and environmental pollution cost, and recommendations are given for cities to build M-ULS.

II. STUDY DESIGN

Based on existing research, this paper designs a metro-based underground logistics construction scheme to explore the feasibility and effectiveness of building the M-ULS model.

Firstly, this study uses existing metro stations in the city as underground logistics nodes and identifies demand points based on the city's economic activity concentration. The demand points were first classified into different categories using K-mean clustering in Python, and in each category, the optimal path was solved by implementing a genetic algorithm through MATLAB. On this basis, route planning is carried out for conventional ground transport and M-ULS transport. According to the actual situation. In this paper, we assume the same conditions for the conventional ground transportation and the ground transportation part of M-ULS.

Secondly, this paper proposes a specific retrofitting scheme for the general regular metro stations. The original metro platform will be transformed into a symmetrical passenger and freight platform. The loading and unloading of cargoes are first completed by setting up a pallet-type automatic transport area and a temporary storage area, then the cargoes are transported from the underground logistics node to the surface utilizing a freight elevator, and finally, the cargoes are distributed to the demand point by road transport in trucks. Based on the plan design, this paper simulates the operational flow and operational efficiency of the underground logistics node in AnyLogic simulation software by designing the actual parameters.

Finally, based on the results of AnyLogic simulations, this paper compares conventional surface transport with M-ULS transport in terms of carbon emissions, time costs, fuel costs and environmental pollution costs. The paper then calculates the reduction in emissions and consumption in various aspects of building M-ULS and analyses the benefits of building M-ULS for the city in terms of energy saving and environmental management.

This paper takes the city of Chongqing in China as the subject of study. As of February 2023, Chongqing has completed 11 lines with an operational mileage of 501km, covering almost the majority of the central city area. The cumulative passenger volume of the entire network reached 8.43 billion passengers, with a maximum daily passenger volume of 4.243 million. With a passenger volume of 910 million in 2022, accounting for 42% of public transport trips, it has constituted the world's largest mountainous urban rail operation system. In addition, the geological structure of the central Chongqing area is an arc-shaped folded belt in southeast Sichuan, and the stratigraphic structure is mostly high-strength bedrock, making underground space development less risky. The overall topography of the central city is undulating and the relative height difference is mostly between 15∼40m, which is very suitable for concentrated and high-intensity underground and semi-underground space development and construction [37]. All this provides a good basis for building M-ULS in Chongqing.

III. RESEARCH METHODS

In this paper, we first use the K-mean clustering algorithm to classify demand points into different categories, then solve the optimal path in each category by genetic algorithm, and finally plan the paths for conventional ground transportation and M-ULS transportation. Seven metro lines in central Chongqing use 6As trains, so the models selected for this study are all 6A metro lines. The study area is shown in Figure 1. In this paper, three metro lines with a wide radiation range are selected for the study, and the number of distribution centres near these three metro lines is three. The 3 metro lines are denoted by Subway1, Subway2 and Subway3. The logistics network includes a total of 2 metro transit stations and 30 metro stations. Some scholars believe that the profits brought by express delivery are the most significant when designing an underground logistics comprehensive pipeline corridor [16], so this paper mainly uses express data as a reference when studying distribution. The study selected 61 logistics demand points distributed around the logistics network based on the concentrated distribution of economic activities in the city. To facilitate observation and calculation,

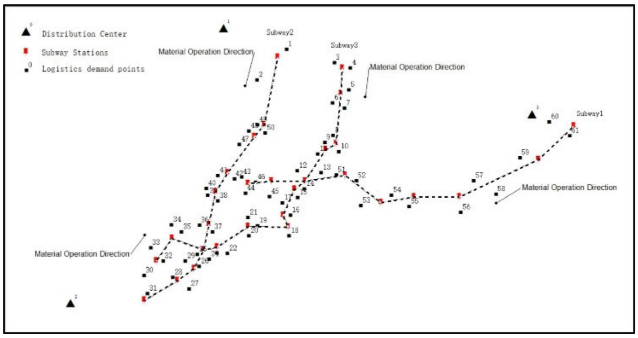


FIGURE 1. City logistics demand points, metro stations and route maps.

we use ArcGIS to present distribution centres, metro routes and demand points, as shown in Fig.1.

A. PATH PLANNING BASED ON THE K-MEAN CLUSTERING ALGORITHM AND GENETIC ALGORITHM

1) CONVENTIONAL GROUND TRANSPORT ROUTE PLANNING

Cargo is mainly transported by road within the central areas of Chongqing. Vehicles depart from each distribution centre and deliver materials to each demand point according to a planned route. This study first uses the K-mean clustering algorithm to divide the sample points and establish a distribution range starting with each distribution centre.

Since its introduction by MacQueen, J., the K-mean clustering algorithm has been continuously optimized and refined [38]. K-mean clustering is used to cluster unlabeled data sets, using the distance from the sample points to the cluster centre as the optimization objective, so that the similarity between samples of the same class is as high as possible, and the similarity between different classes is as low as possible [39]. The basic steps of the K-mean clustering algorithm are as follows [40]:

(1) Determine the number of classes K to be clustered and choose K samples at random to represent the centre of clustering for each class.

(2) The distance from each sample point to the centre of the cluster is calculated and each sample point is assigned to the nearest class based on the magnitude of the distance. K-mean clustering usually classifies samples in a dataset based on the Euclidean distance, the smaller the Euclidean distance, the higher the similarity between the sample points and the cluster centre, and the better the clustering effect [41]. Euclidean distance is calculated as follows:

$$d_{ij} = \sqrt{\left[\left(x_{i1} - x_{j1}\right)^2 + \ldots + \left(x_{in} - x_{jn}\right)^2\right]} \tag{1}$$

where d_{ij} is the Euclidean distance, x_i, x_{jn} is the sample points.

(3) Recalculate the mean of the samples within each class to form new clustering centres.

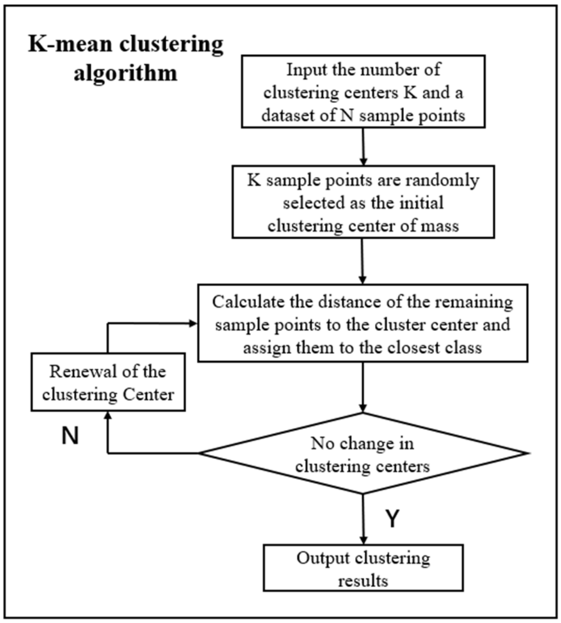


FIGURE 2. K-mean clustering algorithm process.

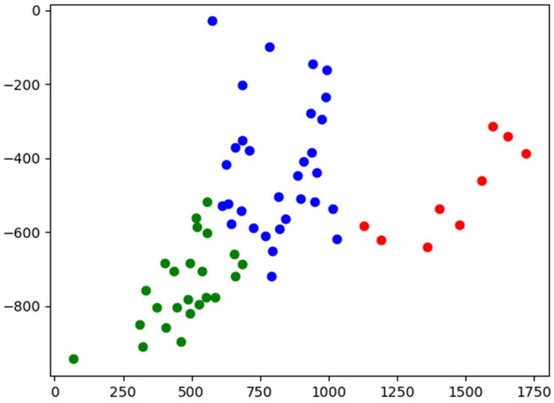


FIGURE 3. K-mean clustering result.

(4) Repeat steps 2 and 3 until the sum of squares of errors for all samples converge:

$$E = \sum_{I=1}^{K} \sum_{n \in C_i} |n - m_i|^2 \tag{2}$$

where E is the sum of squares of errors for all sample points and n is the sample point, m_i is the mean of class C_i.

Combining the geographical locations of the three distribution centres in the western, northern and eastern parts of the central city, a cluster analysis was carried out by making the K = 3. The K-mean clustering algorithm is implemented in Python, the computational flow is shown in Fig.2 and the output is shown in Fig.3. The different classes are represented in blue, red and green respectively.

Based on the K-mean clustering results, the sample points were divided into 3 classes. For the convenience of the subsequent study, the blue class was noted as class A, the

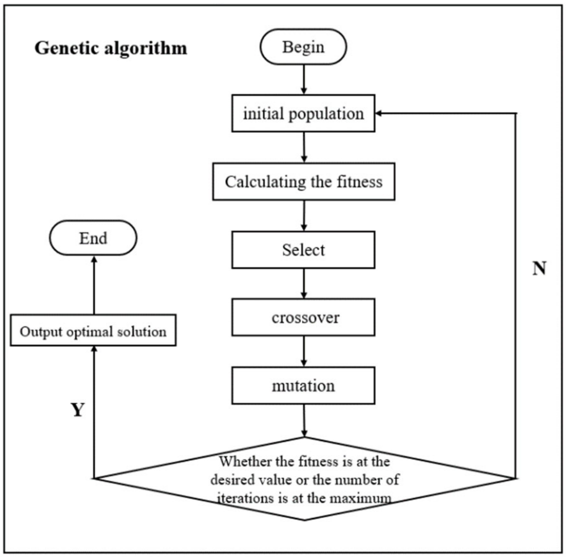


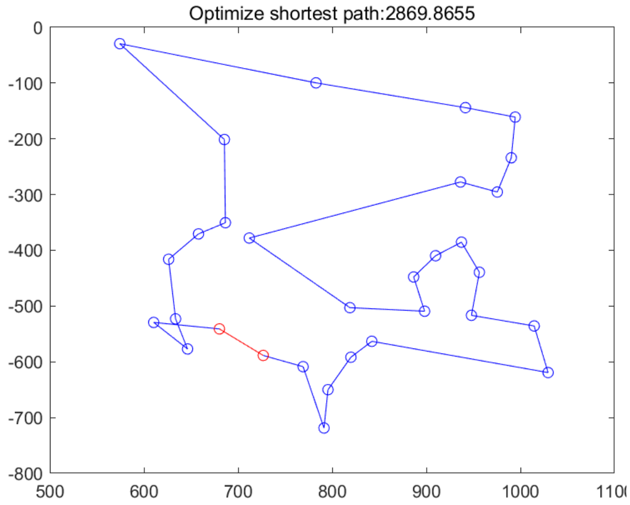
FIGURE 4. Genetic algorithm process.

green class as class B and the red class as class C in the subsequent study. In studies of ground transportation, some scholars have directly used the distance from the distribution centre to each demand point as the total distance travelled for ground transportation [42]. In this paper, optimization is carried out on this basis, using genetic algorithms to solve an optimal path for each class.

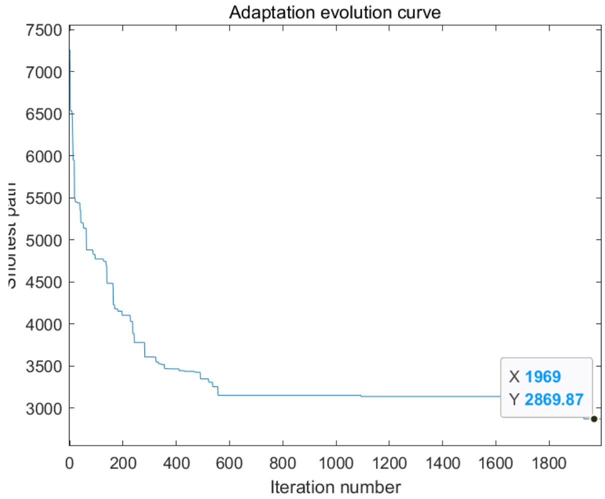
The genetic algorithm is a computational model that simulates the Darwinian biological evolutionary process of natural selection, survival of the fittest, and natural elimination, proposed by American professor J. Holland in 1975 [43]. The basic idea is to encode each possible solution to the problem being solved as a chromosome. All chromosomes form a population, and individuals are selected based on each individual's fitness in the initial population to produce the next generation, which is recombined through crossover and mutation operations to obtain a new population. As the new population inherits the good traits of the previous generation's population, it has better performance, allowing the population to evolve toward the optimal solution [44]. The computational flow of the genetic algorithm is shown in Fig.4 [45]:

According to existing research [46], this paper sets the number of genetic generations to 100, the population size to 200, and the maximum number of iterations to 2000. The number of iterations is represented on the x-axis and the shortest path is represented on the y-axis. The genetic algorithm was implemented in MATLAB and the output is shown in Fig.5, 6, and 7. The shortest path in the figures below corresponds to the coordinate system in ArcGIS.

Class A optimization results show that when the number of iterations reaches 1969 there is a shortest path $Y_A = 2869.8655$; Class B optimization results show that when the number of iterations reaches 973 there is a shortest path $Y_B = 1997.7276$; Class C optimization results show that when the number of iterations reaches 33 there is a shortest path $Y_C = 1413.56$. According to the results of the genetic algorithm, the adaptation degree evolution curve shows that all have achieved the shortest path planning. The total route planned for conventional ground transportation is shown in Fig.8, with a total distance of 173.66km.



(**a**) Class A optimizes the shortest path

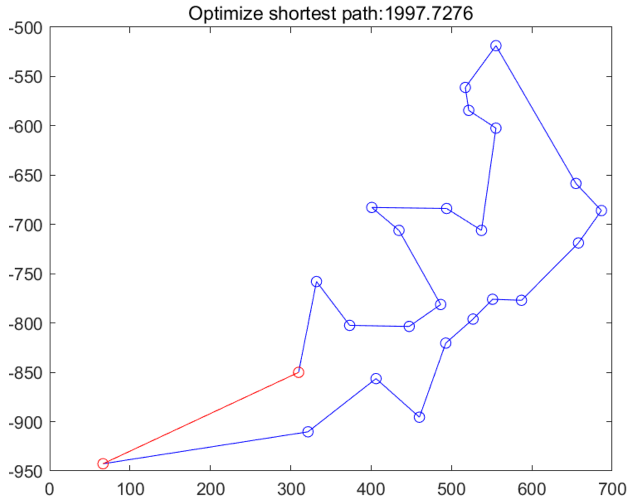


(**b**) Class A adaptation evolution curve

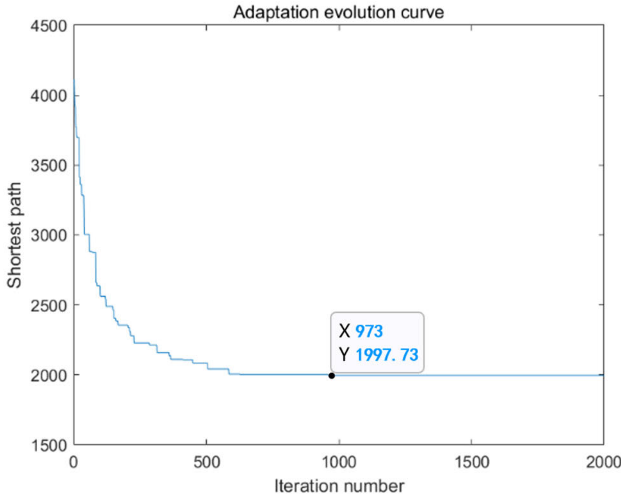
FIGURE 5. Class A output results.

2) M-ULS TRANSPORT ROUTE PLANNING

The M-ULS transport method starts by sending the cargo from the distribution centre to the nearest metro station, transporting them through the existing metro lines, and then transferring them to the ground for road transport once they reach a metro station close to the point of logistics demand. A K-mean clustering method is first used to classify the demand points that can be served by a metro station, and then a genetic algorithm is used for planning. The calculation process is the same as above. The results of the route planning are shown in Fig.9, with a total distance of 80.03km. The M-ULS



(**a**) Class B optimizes the shortest path



(**b**) Class B adaptation evolution curve

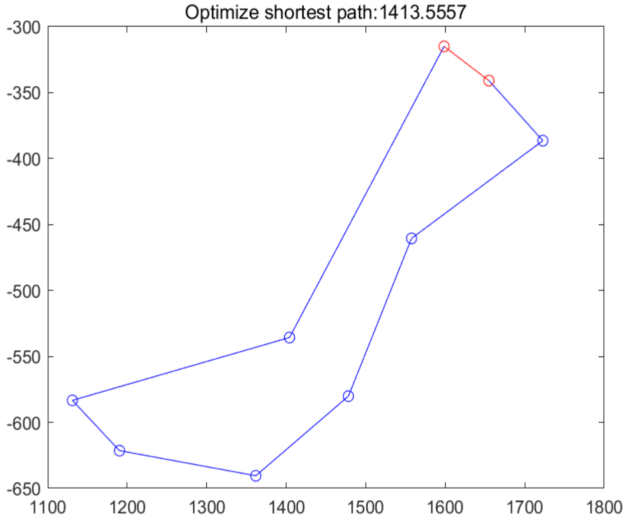
FIGURE 6. Class B output results.

transport model reduces the pressure on ground transport on a large scale compared to conventional ground transport.

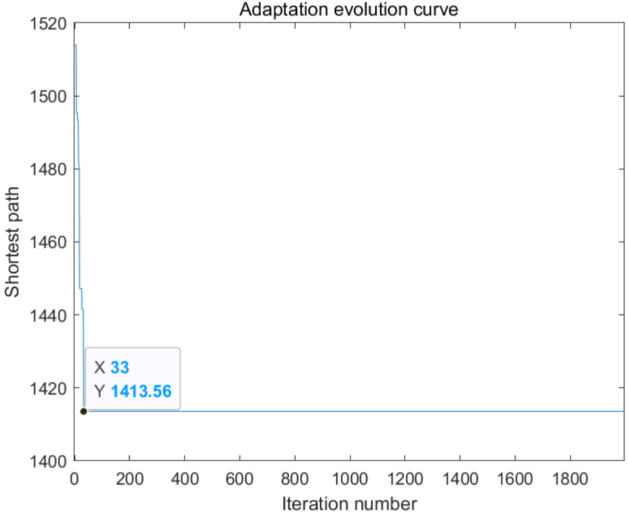
B. M-ULS NODE SPACE TRANSFORMATION

1) M-ULS NODE PLAN DESIGN

M-ULS needs to be built from the distribution centre to the point of demand. The cargo is sorted at each distribution centre, stacked on pallets, and loaded into different logistics bins according to the demand point they belong to. The logistics bins are set up in different panels according to the properties and size of the cargo. Radiofrequency identification tags (RFID) are attached to the bins and pallets to provide real-time information on the location, arrival, and transit of the logistics cargoes. Once the underground logistics node is reached by metro, the cargoes to be distributed at the node are unloaded by the pallet-based automatic transporter, transferred to the cargoes ladder, and transported to the ground terminal, where they are delivered by truck to the demand point via road transport. A temporary storage area is provided in the automatic pallet transport area for the temporary storage of cargo.



(**a**) Class C optimizes the shortest path



(**b**) Class C adaptation evolution curve

FIGURE 7. Class C output results.

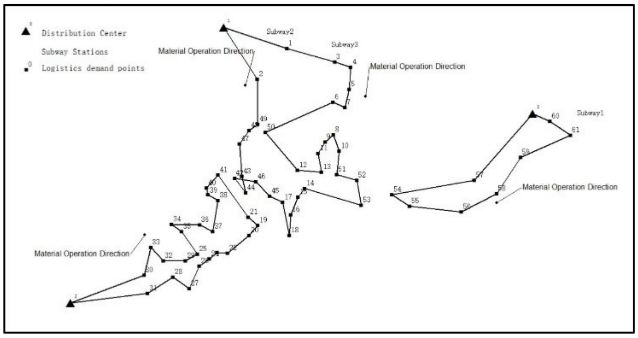


FIGURE 8. Shortest route planning for conventional ground transport.

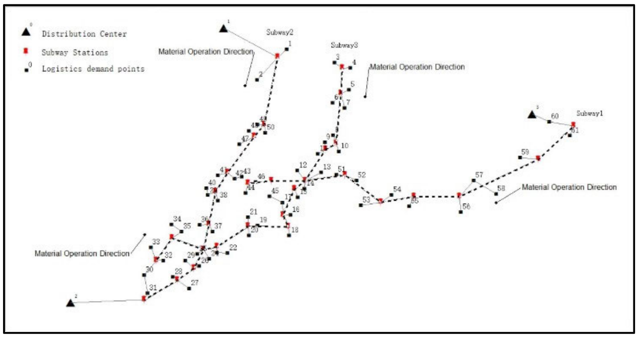


FIGURE 9. M-ULS transport shortest path planning.

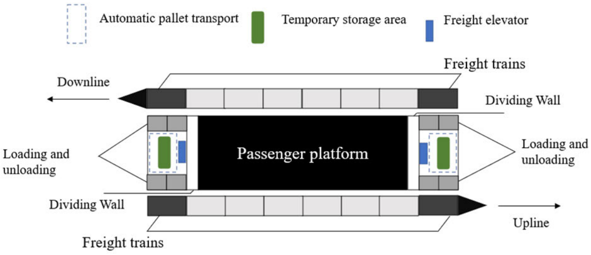


FIGURE 10. Symmetrical platform transformation design.

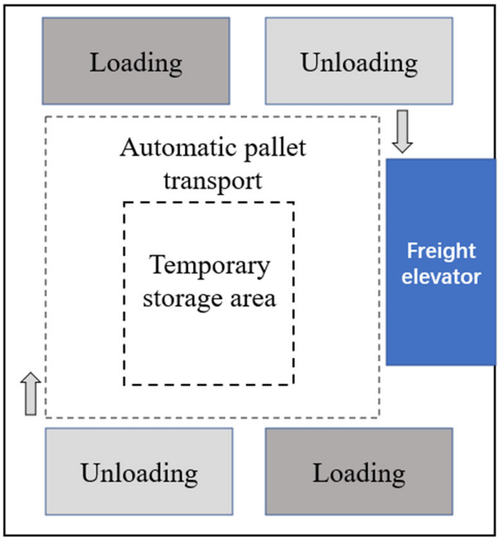


FIGURE 11. Automatic pallet transport process.

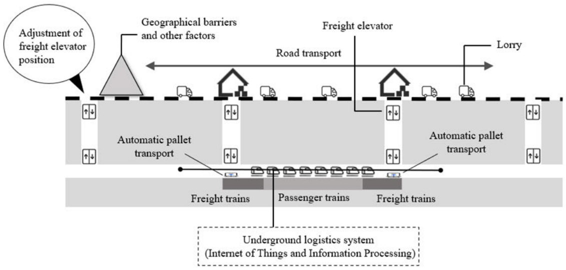


FIGURE 12. Longitudinal view of the design of the underground logistics node transformation.

M-ULS transport can be modelled on railway passenger and freight co-transportation, with three main types of passenger and freight separate lines, metro external carriages, and separate logistics trainsets [42]. The metro network in the central city of Chongqing is more mature and covers the vast majority of the area, and the intensity of passenger traffic in the Chongqing metro is such that the use of separate logistics trains has a greater impact on passenger transport. Therefore, in combination with Chongqing's unique 6As model, this paper chooses the form of external underground carriages for passenger transport co-location for research. This transformation method has the advantages of less transformation, less influenced by external factors, higher safety, and good energy saving and emission reduction performance.

In the current study of underground logistics in the form of passenger and freight common lines, there are two main types of transformations of metro platforms: symmetrical platform distribution and diagonal platform distribution [21]. The symmetrical platform is designed with four logistic aisles at diagonal positions in the passenger area for the more standard metro platforms, allowing for a more concentrated area for loading and unloading cargo. Combined with the 6As model of Chongqing Metro, which is suitable for adding cargo trains at the beginning and end of passenger trains, this paper chooses to transform the platform into a symmetrical platform. The separation of the passenger and freight platforms by a dividing wall reduces the range of safety problems associated with passenger and freight interference, in line with the principle of safety. The degree and difficulty of modification are minimal, in line with the principle of minimal cost. This type of transformation is a lesser degree of modification to the original underground and allows for full use of the underground space. The transformation design is shown in Fig.10.

Part of the research design of the ULS using AGVs to sort cargo unloaded from trains [21]. However, the use of AGVs would make the cost of retrofitting too high and would require high technology and equipment requirements. Therefore, this paper suggests that the sorting of cargo can be done in the distribution centre and that AGVs are no longer used for sorting at underground logistics sites. After arriving at the underground logistics node, the cargoes are transported by automatic pallet transport to the freight elevator and transferred to the surface for road transport by truck to the point of demand. The automatic pallet transport process in the loading and unloading area is shown in Fig.11 and the vertical transformation of the underground logistics node is shown in Fig.12.

The number of carriages and their internal structure had to be redesigned to take into account the transformation of the station and the efficiency of the freight. Two additional freight carriages were added to the existing "5 moving and 1 towing" train, creating a "7 moving and 1 towing" passenger and freight train. According to the "Construction Standards for

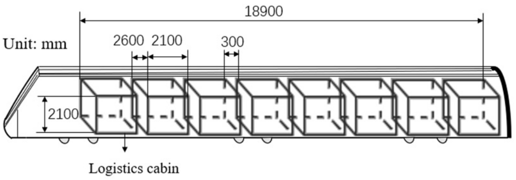


FIGURE 13. The layout of the freight carrier.

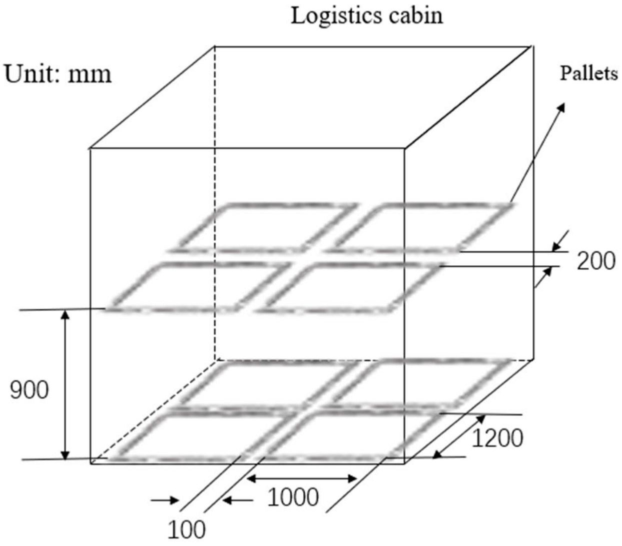


FIGURE 14. The internal layout of the logistics cabin.

Urban Rail Transit Projects'' approved and released by the Ministry of Construction of the People's Republic of China and the National Development and Reform Commission for rail transit, a freight carriage can be added at the beginning and end of each of the 6As model (19.0m long, 3.0m wide and 3.8m high). Each carriage is designed with 8 logistics cabins (2.6m×2.1m ×2.1m), with each logistics by taking a metro parking tolerance spacing of 30cm between them [21]. the structural layout of the freight carrier is shown in Fig.13.

According to the ''Opinions on Promoting Standard Pallets for Unitized Logistics'' issued by the Chinese Ministry of Commerce, pallets of 1.2m x 1m are designated as the preferred specification and are most commonly used in China [47]. This paper is designed to place 8 (1.2m×1m×0.15m) pallets in each logistics cabin. The underground stopping time is short and for fast loading and unloading of cargoes, the underground logistics node takes a single entire pallet entry and exit mode. Each time the metro arrives at the station the automatic pallet transport is operated only twice, one out and one in. The longitudinal design allows for rapid loading and unloading of cargoes at the underground logistics node and their transfer to the surface for transport. The internal layout of the logistics cabin is shown in Fig.14:

2) M-ULS SITE ANYLOGIC SIMULATION

Due to the difficulty of construction and realistic conditions, it is difficult to verify underground logistics systems in practice. To practically simulate the operational flow and efficiency of the M-ULS, this paper uses Anylogic to simulate the nodes of the underground logistics.

TABLE 1. Values for automatic pallet transport parameters.

Parameter	Max. speed(m/s)	Max. speed around bends(m/s)	Acceleration(m/s^2)	Deceleration (m/s^2)	Path calculation delay(s)	Delay to resume movement(s)	Loading and unloading times(s)
Values	1	0.8	1	1	2	2	20

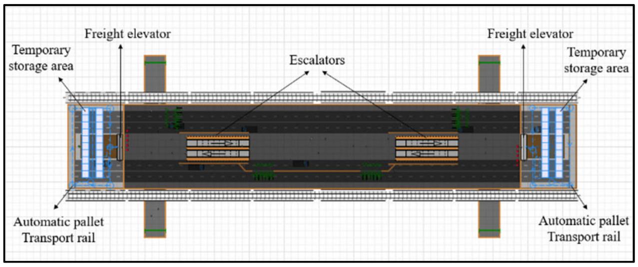


FIGURE 15. 2D simulation model of the M-ULS node.

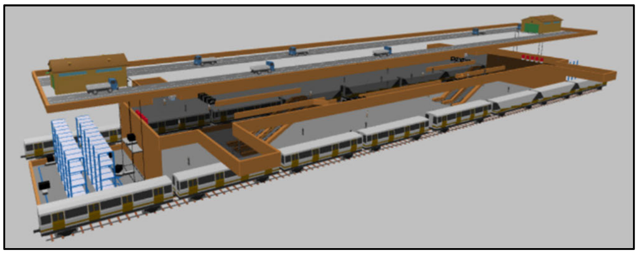


FIGURE 16. 3D simulation model of the M-ULS node.

This paper investigates the operational efficiency of the transformed M-ULS by simulating the stopping time of wagon trains, automatic pallet transport, and the transport of freight elevators. According to the actual working of the metro and freight elevator, the parameters for setting the automatic pallet transport and freight elevator are taken as shown in Table 1 and Table 2.

The simulation design in AnyLogic is shown in Fig.15 and Fig.16. In this paper, three levels are designed, one basement level, the second basement level, and the ground level. The first basement level is the ticket hall, where pedestrians purchase tickets, go through security checks and check in, and take the escalator to the second basement level to board the underground. The second basement level is the station platform, where pedestrians disembark and disembark passenger trains on the passenger platform and take the escalator to the first basement level to exit the station. Cargo is loaded and unloaded at the freight platform and transported by escalator from the second basement level to the ground level. The ground floor is used for road distribution by truck from the underground logistics node to the point of demand.

TABLE 2. **Value of freight elevator parameters.**

Parameter	Increase speed(m/s)	Descent speed(m/s)	Pick up time(s)	Put down time(s)	Loading and unloading times(s)
Values	0.15	0.1	2	2	10

TABLE 3. **Metro operating parameters.**

Parameter	Passenger flow（ten thousand people /day）	Running time	Interval Departure Time（min）	Total daily one-way trips
Subway1	2.54	6：30-22：30	10	96
Subway2	2.23	7：30-20：30	7	112
Sbway3	10.81	6：30-23：00	9	110

The average train stopping time is 1min, the interval between train departures is taken as 8min and the depth of the metro station is taken as 20m. The simulations show that the existing design takes 24 min to transport all the cargo in a freight carrier to the ground, o that every three trains are loaded and unloaded by the automatic pallet transport.

C. EVALUATION OF M-ULS

Chongqing is the most congested city in mainland China, according to a report published by TomTom in 2018. With an average congestion index of 44%, Chongqing is ranked 18th in the world and has a serious traffic congestion problem. Traffic congestion not only consumes residents' time but also increases the amount of fuel and pollution consumed by motor vehicles. Combining the output of AnyLogic software with existing data, this paper evaluates the sustainability of M-ULS in terms of carbon emissions, time costs, fuel costs, and environmental pollution costs.

Before the sustainability evaluation, the parameters of the M-ULS were first determined based on the operation of the metro lines in Chongqing. According to the official website of Chongqing Municipal Railway Transportation (Group) Co.,[1] the daily passenger flow, running time, interval departure time, and number of metro trips are shown in Table 3. Since the main function of M-ULS is to transport materials from distribution centres to residential and commercial areas, and the relatively small amount of cargo transported from residential and commercial areas to distribution centres, only one-way transport from distribution centres to demand points is considered in the evaluation.

The maximum capacity of the 6As metro train is 2322 passengers in 6 carriages, assuming an average weight of 65 kg per person. then the load capacity of each carriage is 2.52 tons, and the load capacity of each logistics cabin can be set to 315 kg. the parameters of the logistics cabin are shown in Table 4.

TABLE 4. **Logistics cabin parameters take values.**

Parameter	Logistics cabin specifications(m)	Logistics cabin spacing(m)	Logistics cabin weight limit(kg)	Pallet specifications(m)
Values	2.5×2.1×2.1	0.3	315	1.2×1×0.15

According to the statistics for 2022, the annual express delivery per capita in Chongqing is 33.98 pieces.[2] Because of the high population density in the central area, the total annual courier demand in the study area of this paper is 84.95 million pieces, taking the logistics network that can serve a population of 2.5 million as an example.

According to the China Express Locker Industry Market Research Report 2020, Feng Chao's market share of express lockers is 55%, so this study uses the large compartment size (0.45m×0.37m×0.29m) of Feng Chao's express lockers, which can meet the needs of most cargo sizes, as the average volume of cargo [42]. The annual volume of couriers to be transported by the distribution centre is then 4.1018 million m^3. As can be seen from Table 3, the total number of daily one-way transport trips for the logistics network studied in this paper is 318 train trips. Combined with the loading and unloading efficiency of pallet-type automatic transport, set to every three trips loading and unloading cargo, then the total number of daily one-way unloading of freight cars is 212 cars. The annual volume of cargo that can be transported is 5.3486 million m^3.

1) CARBON EMISSIONS

The traditional ground transportation is the distribution from the suburbs to the city, mainly using 6.8m type trucks with carriage size of 6.8m×2.4m×2.6m, carrying volume of 40 m^{3,} and weight limit of 10 tons. From the end of the underground logistics to the final demand point is the short distance distribution within the city, mainly using 4.2m type trucks, carriage size 4.2 × 1.6×1.8m, the load volume of 12 m^3, weight limit 2.5 tons.

In the metro routes and demand points studied in this paper, it is clear from the above path planning that the total distance travelled by traditional ground transport after optimization is 173.66km and the total distance travelled by M-ULS is 80.03km. the express volume of the distribution centre for a full year in 2022 is 4.1018 million m^3, requiring 96,668 vehicle trips to be delivered by 6.8m type trucks and 4.2 type trucks to deliver 339,105 trips.

The fuel consumption of a 6.8m type truck under full load is about 30L per hundred kilometres. Traditional ground transportation is caused by truck fuel consumption of 5.0362 million litres per year. 4.2m type truck fuel consumption of 100km under full load is between 10L and 18L, because Chongqing has more mountainous roads, but the

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[1] Chongqing Rail Transit(GROUP)CO. (http://www.cqmetro.cn)

[2] Statistical Bulletin on National Economic and Social Development of Chongqing Municipality in 2022 Chongqing Municipal People's Government (http://www.cq.gov.cn)

TABLE 5. **Coefficient parameter values.**

Parameter	V_h(KJ/kg)	C_v(kg/GJ)	C_c(kg/per unit)
Values	42，652	72.6	3.097

road condition is better, so take 100km fuel consumption of 15L. M-ULS ground transportation part of the truck fuel consumption of 4.0708 million litres per year. Based on the calculated fuel consumption of road transport trucks, the carbon emissions of trucks can be calculated. The detailed calculation formula is as follows [48]:

$$C_T = \sum_{a=1}^{b} m_a \times C_c \tag{3}$$

where C_T represents the total carbon emissions, m_a represents the transportation fuel consumption in the region, C_c represents the fuel carbon emission factor, b represents the number of energy types only diesel trucks are studied in this study, so b is taken as 1). C_c is calculated as follows:

$$C_c = V_h \times C_v \div 1000, 000 \tag{4}$$

where V_h is the calorific value of energy (average low-level heat generation), C_v is the effective mission factor per unit of heat generated CO_2. The selection of parameters such as fuel carbon emission factors is shown in Table 5 [49]. Calculations show that conventional surface transport emits 13,101.6 tons of carbon per year and M-ULS emits 10,590.1 tons of carbon per year.

2) TIME COSTS

Time costs can be understood as a monetary representation of the amount of benefit added due to the passage of time and the amount of benefit lost due to the unproductive consumption of time [36]. It has been shown that the time value of freight is mainly related to transport time [50]. This study argues that the time costs arising from traffic congestion are mainly related to the time value of freight items. The value of freight is also highly correlated with the time cost of transportation, as cargoes of different values vary in their sensitivity to time during transportation. Time costs are calculated by the following formula [24]:

$$C_t = V_F \times \frac{\rho}{24} \times T \tag{5}$$

where C_t is the cost of time, V_F is the value of the cargo ρ is the sensitivity of the cargoes to time, T is the time of transport. According to calculations by the China Post Office, the courier industry has grown rapidly in recent years but there has been more growth in the lower value of these couriers, so for this paper, the average value of a courier is RMB 140.Rho takes a value of 26% [51]. Transport time is the transport distance divided by the average speed of motor vehicles in the central city of 23.7km/h. The results show that the annual cost of time spent on traditional surface transport due to traffic congestion is RMB 960.381 million and the annual cost of time spent on M-ULS due to traffic congestion is RMB 435.069 million.

3) FUEL COSTS

The M-ULS has significantly fewer miles of ground transport than conventional ground transport, which will significantly reduce the fuel consumed by transport trucks. Some scholars have studied the relationship between fuel consumption and traffic congestion and found that vehicle speed had a significant effect on fuel consumption, with the average fuel consumption of the vehicle being at a lower level when the vehicle was travelling at 50 to 85km/h [52]. Under congested conditions, it is clear that more energy is consumed, mainly about the total mileage of the congested road, the energy consumption coefficient of the vehicle under congested and open conditions respectively, and the price per unit of fuel. The calculation formula is as follows [51]:

$$C_F = C_f + C_e \tag{6}$$

where C_F is the cost of fuel, C_f is the cost of fuel consumption, C_e is the cost of additional fuel.

$$C_e = \frac{S_c}{100} \times (V_c - V_p) \times Y_f \tag{7}$$

where S_c is the congested mileage, V_c is the energy consumption index of motor vehicles under congestion, V_p is the energy consumption index of motor vehicles under smooth traffic, Y_f is the fuel price. Referring to Wei et al.'s study [24], the values of V_c are taken as 69.2(L/100km), V_p as 51.56(L/100km) and Y_f as the average diesel price of RMB 8437.4 per ton in Chongqing, China 2022. Traffic congestion is assumed to be caused by the full transportation process for both the surface transport trucks and the surface transport portion of the underground logistics system. The results show that the fuel cost spent on surface transport is RMB 36.204 million and the fuel cost spent on the M-ULS is RMB 29.232 million.

4) ENVIRONMENTAL POLLUTION COSTS

Traffic congestion takes more time on the road and consumes more fuel than smooth traffic, which undoubtedly emits more emissions. These emissions include mainly greenhouse gases (CO_2) and air pollution gases. At the same time, congestion from motor vehicles can cause more noise pollution in cities, a part that has been less considered in previous studies. The cost of environmental pollution is calculated as follows:

$$C_p = C_{co_2} + C_w + C_n \tag{8}$$

where C_p is the cost of environmental pollution, C_{co_2} is the cost of treating CO_2, C_w is the cost of treating air pollution gases, C_n is the cost of treating noise pollution.

According to the China Carbon Market Research Report 2022 published by China Ecology Network, the carbon emission trading price of RMB 45.61 per ton is used to calculate the treatment cost of CO_2.[3] The specific calculation formula is as follows:

$$C_{co_2} = C_T \times P \tag{9}$$

The results show that the cost of CO_2 treatment due to conventional surface transport is RMB 0.5976 million, and the cost of CO_2 treatment due to the surface transport component of underground logistics is RMB 0.483 million. The cost of treating atmospheric pollution gases is calculated as follows [24]:

$$C_w = R \times E \times \frac{M_c}{M_{st}} \tag{10}$$

where R is the proportion of motor vehicle pollutants to total air pollutants, E is the economic loss from motor vehicle air pollution, M_c is the air pollutant gas emissions from additional congestion, M_{st} is the total social air pollutant gas emissions. The results show that the cost of treating air pollution caused by conventional ground transportation is RMB 1.4521 million and the cost of treating air pollution caused by M-ULS due to traffic congestion is RMB 1.1736 million.

The noise pollution studied in this paper refers to the sound produced by motor vehicles in operation that disturbs the surrounding living environment. In existing social surveys, it has been shown that nearly 40% of the respondents consider road traffic noise to be serious or very serious [53]. Li Jinping et al. investigated residents' willingness to pay for environmental quality improvements using a conditional valuation method, which showed that the economic loss caused by noise pollution accounted for about 3.6% of respondents' average monthly income [54]. The formula for calculating the cost of treating noise pollution is therefore as follows:

$$C_n = 3.6\% \times N \times PCDI \tag{11}$$

where N is the population of the region covered by the logistics network studied in this paper, taking the population of the central city of Chongqing as 10.4776 million, $PCDI$ is the annual disposable income of residents, according to the 2022 Chongqing National Economic and Social Development,[4] the disposable income of urban residents in Chongqing in 2022 is RMB 45,509. The results show that the cost of dealing with noise pollution caused by traffic congestion in the central areas of Chongqing is RMB 171.657 billion. According to the data published by the Chongqing Municipal Institute of Transportation Planning, the total road mileage in the central city of Chongqing is 6025.9 km. the total mileage of conventional surface transport optimized for the study area of this paper is 173.66 km, resulting in a noise pollution cost of RMB 494.697 million, and the total mileage of M-ULS transport is 80.03 km, resulting in a noise pollution cost of RMB 227.978 million. A comparison of the data for the four indicators for conventional surface transport and M-ULS is shown in Table 6.

TABLE 6. **Comparison of the results.**

Evaluation	Carbon emissions (tons/year)	Time costs (CNY 10,000/year)	Fuel costs (CNY 10,000/year)	Environmental pollution costs (CNY 10,000/year）
Conventional ground transport	13,101.6	96,038.1	3,620.04	49,674.7
M-ULS transport	10,590.1	43,506.9	2,923.2	22,963.4
Savings percentage	19.17%	54.7%	19.25%	53．78%

IV. DISCUSSION

The study in this paper concluded that waste emissions after the completion of the M-ULS were approximately 80.83% of those of conventional road transport. The results of a study by Hai et al. showed a 16-28% reduction in waste emissions from highways in the Waigaoqiao area of Shanghai, China, after the completion of the ULS [55], which is similar to the findings explored in this paper.

Based on the results of existing studies, this paper extends the conclusions to all rail transport in the central city of Chongqing. According to the transformation method of adding cargo trains at the beginning and end, the transport efficiency of loading and unloading once every three trains, then the central city can transport 941,700 freight cars per year. Taking the three metro lines studied in this paper as a reference, the M-ULS system can reduce carbon emissions by 2511.5 tons per year, which means that Chongqing's rail transport can reduce carbon emissions by 30,564.9 tons per year after all the lines are converted to the M-ULS mode. This indicates that the establishment of M-ULS can reduce carbon emissions to a certain extent. According to the China carbon emission data published by Multi-resolution Emission Inventory for China for 2019-2021, the weighted moving average method was used to calculate the total carbon emission in Chongqing in 2022 as 144.805 million tons, and the conversion of all rail transport to M-ULS could reduce Chongqing's carbon emission by 0.02 ‰ of carbon emissions. As rail transport is only located in the central areas of Chongqing and the study in this paper only focuses on the transport sector, the amount of carbon emission reduction accounts for a small proportion of the carbon emissions of the whole city of Chongqing.

The full completion of M-ULS will save RMB 9.6 billion per year in costs due to traffic congestion, representing 0.33 ‰ of Chongqing's GDP in 2022 (RMB 2,912.903 billion). The largest proportion of the total cost is time costs (64.3%), followed by environmental pollution costs (33.3%) and the smallest proportion is fuel costs. The cost of congestion is reduced by around 50% compared to

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[3] China Carbon Market Research Report 2022 - EcoChina.com (http://www.eco.gov.cn)

[4] Statistical Bulletin published by Chongqing Municipal Bureau of StatisticsStatistical Bulletin on National Economic and Social Development of Chongqing in 2022 - Chongqing Municipal Bureau of Statistics(http://tjj.cq.gov.cn)

conventional transport after the construction of the M-ULS. It can be concluded that the construction of the M-ULS is very effective in reducing regional traffic congestion losses. In other scholars' studies on cost issues, for example, Qi et al. studied that the cost of travel time for the whole society in Beijing in 2005 was about 14.83% of Beijing's GDP in 2005, and the cost of time lost due to travel was high [56]. In the study in this paper, the cost of travel time as a proportion of GDP is small as only the cost of travel time due to the increased number of vehicles for freight transport in the central city of Chongqing is considered. Dong et al. concluded that congestion losses could be reduced by approximately 28% under high-density ULS conditions [35]. The congestion loss in Dong et al.'s study is related to the delay time and the value of personnel time. The study in this paper also takes into account fuel consumption and environmental pollution, so the percentage savings are greater than their findings.

V. CONCLUSION

To alleviate the environmental pollution and cost increases caused by traffic congestion in China's major cities, this paper investigates the feasibility and effectiveness of building M-ULS in Chinese cities. This paper proposes a holistic approach to the construction of M-ULS from route planning, to the design and actual simulation of metro station modifications, to the evaluation of benefits. The study of three metro lines in Chongqing concluded that the carbon emission level and fuel consumption after the completion of ULS is about 80% of that of conventional surface transport, and can reduce the time cost and environmental pollution cost by about 54%. In addition to this, a large number of road freight vehicles and logistics node facilities can be saved, reducing human cost, which accounts for the highest percentage of logistics transportation. It shows that the M-ULS construction scheme proposed in this paper can effectively reduce the cost of environmental pollution and traffic congestion consumption, and reduce carbon emissions to a certain extent, which has good economic and environmental benefits.

Therefore, this paper makes the following recommendations for the city to build M-ULS: Firstly, the city government should plan the layout of M-ULS in an integrated manner and reasonably determine the layout of underground logistics space and route arrangements. Secondly, design the realization plan of M-ULS according to local conditions, reasonably control the transformation cost and reduce the transport risk. Third, coordinate the types and quantities of cargo transported by urban road transport and M-ULS to build an efficient integrated logistics transport system incomprehensively Fourth, improve the carbon reduction capacity of the underground logistics and transportation system and reduce environmental pollution caused by transportation to enhance the sustainable development of the city.

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