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Discussion on the Environmental Impacts of Logistics in a Spatiotemporal Framework

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Abstract: In the era of globalization and e-commerce, urban logistics continues to grow, which has been accompanied by an increasingly uneven distribution of negative impact on city environment in the highly heterogeneous urban space. Based on the interrelationships and connections among the logistics flow, land use development, and environment, this paper analyzes the logistics environment from different response time. Linking the environmental impacts with supply chain management and public policy formulation, the paper discusses how such impacts can be effectively mitigated through strategies at various spatial scales. The paper indicates that the spatiotemporal framework and evolution would help to evaluate the environmental impacts associated with logistics demand comprehensively. With the advanced big data application techniques, policymakers can better understand the interactions between stakeholders and the path towards sustainable urban logistics in cities with booming demand for commerce and limited public space. **DOI:** 10.13813/j.cn11-5141/u.2021.0202-en

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0 Introduction

The freight movement is an important part of the national economy and one of the core activities of social life. Its sustainable development is related to the potential for economic growth and the improvement of people's living standards. The latest data from the United Nations shows that more than 4.2 billion people, 55% of the world's population live in cities and towns [1]. In order to provide such a large population with a wealth of goods and services in cities, the demand for urban freight has been growing rapidly in the past 20 years. In particular, the rise of e-commerce in the past decade has contributed to the growing demand for serving online shopping customers in addition to supporting industrial and commercial activities. These changes have brought about new challenges to the coordinated and sustainable development of urban transportation systems.

Given the multi-dimensional demand, there has been a dramatic increase in terms of urban freight-related facility, land use and activity intensity in major cities around the world. From 2014 to 2018, the average annual growth rate of the square footage of freight and storage facilities in the five cities of Shanghai, Suzhou, Wuxi, Hangzhou, and Jiaxing in the Yangtze River Delta region was as high as 26% [2]. As a result, although freight facilities and related activities provide a wide range of social benefits, their relevant negative environmental impacts including air pollution, noise, land use inefficiency and fragmentation of urban texture are gradually spreading over the urban space and concentrated in some neighborhoods. These impacts pose a serious threat to the health of local residents and the coordinated development of urban space [3–4].

The "Outline for Building China into A Country with Strong Transportation Network" issued by the Central Committee of the Communist Party of China and the State Council of China in 2019 put forward new requirements for high-quality and sustainable development of urban freight, emphasizing the creation of a green and efficient modern freight system, the promotion of new energy urban freight vehicles, and the strengthening of energy conservation, emission reduction and pollution prevention. In 2020, the National Development and Reform Commission and the Ministry of Transport provided more specific plans and

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expectations for developing sustainable urban freight. According to the trajectories of policy formulation in recent years, the environmental governance of urban freight has become one of the most important policy goals that transport departments at all levels pay attention to.

One of the prerequisites for formulating urban freight planning in line with sustainable development goals is to fully understand the complex impacts of such activities on urban space and accurately analyze innovative policy approaches to alleviate their negative impacts. Based on the empirical results on the relationship between urban freight and the environment in the past 20 years, this article re-examines how freight activities, from a composite perspective of time and space, can generate negative externalities in highly heterogeneous urban space, and ultimately affect the shape, structure and development capacity of cities. On this basis, we discuss the methods of evaluating the environmental impacts from the spatiotemporal perspective and propose suggestions in urban freight planning practices that would benefit the entire society.

1 Understanding the environmental impacts of freight from a temporal perspective

The growth and development of the freight system result from long-term collaboration and competition among a large number of enterprises and individuals, and its interactions with urban land use systems and transportation network systems are complex and multi-dimensional [5]. If people analyze the impacts of urban freight activities on the environment from a static perspective, they may often ignore the dynamic characteristics of this process, thereby underestimating the complexity of public policy formulation and social governance. There are three types of environmental impacts of urban freight activities in terms of response time: namely short-term, medium-term and long-term environmental impacts. Different types of environmental impacts vary in modes of action, scope and mechanism, which are worthy of consideration and attention among urban transportation policy makers.

1.1 Short-term environmental impact

Among the negative environmental impacts caused by urban freight activities, typical short-term environmental impacts include noise, traffic safety threats, and air pollution. The generation and release of these environmental impacts are relatively immediate and rapid. For example, exhaust emissions from freight vehicles, noise during vehicle running and operating, traffic congestion and accidents, etc. all occur simultaneously or immediately with the occurrence and progress of related freight activities. Without considering the further interaction with the natural and built environment or secondary effects, the duration of these impacts is relatively low: the duration of vehicle noise is usually within minutes [6], the basic cycle of the accumulation and dissipation of air pollutants ranges from several hours to tens of hours [7-8], and traffic congestion and accidents usually take no more than one day to resolve [9].

What's corresponding to the immediacy of these environmental impacts is their easy-to-observe characteristics. Pollutants from freight trucks such as black carbon and particulate matter (PM), which have a significant impact on air quality, especially visibility, can be easily identified with eyes. Air pollutants with special odors, including sulfide (SOx), fused ring aromatic compounds, etc., can be strongly perceived by people during the emission process. Concentration monitoring of other colorless and odorless pollutants such as carbon monoxide (CO) and nitric oxide (NO) can be performed by air quality monitoring devices [10]. According to the *China Mobile Source Environmental Management Annual Report* released by the Ministry of Ecology and Environment of China in 2019, various trucks accounted for only 11.1% of the total car ownership, while their proportions in total car emissions of CO, NOx and PM were as high as 32.6%, 72.6% and 84.7% (see Figure 1). Similarly, the monitoring of noise sources and the handling of traffic accidents are also on the routine agendas of departments of environmental protection.

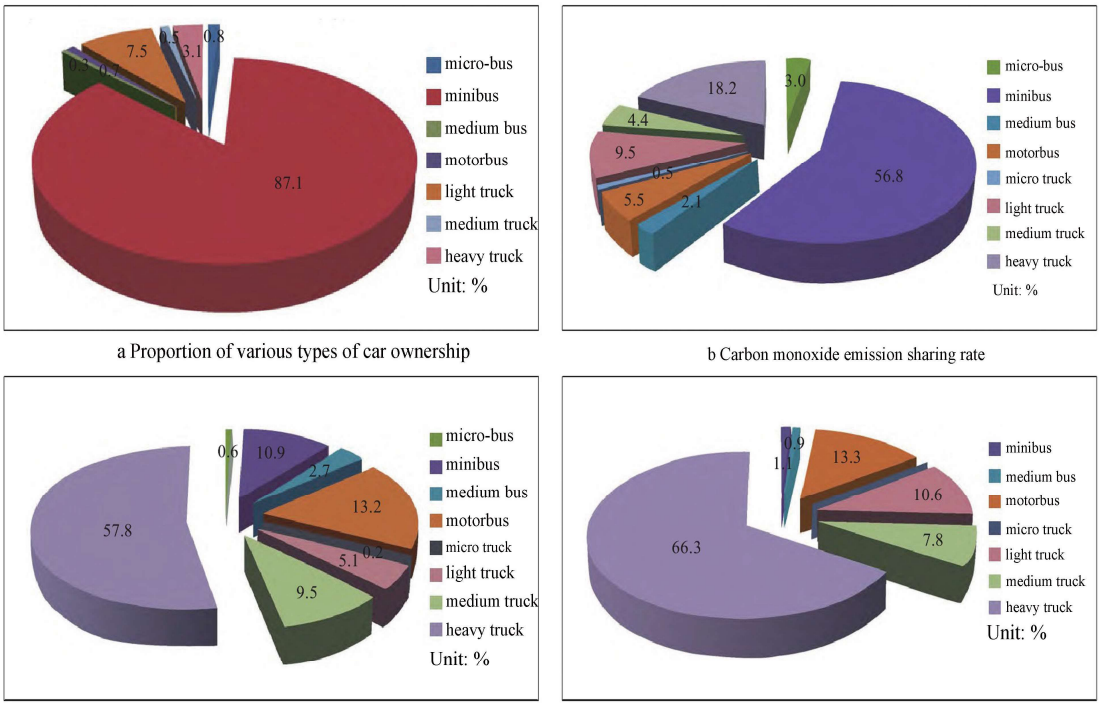
1.2 Medium-term environmental impact

Compared with the above short-term environmental impacts, the medium-term environmental impacts caused by freight activities, including urban heat island effects, land use inefficiency, and ecosystem destruction, are commonly featured by a relatively longer formation process and generate non-intuitive effects [4, 11]. Due to the rapid expansion of freight demand and the continuous extension of freight networks, the impacts of the construction, expansion and reconstruction of freight facilities on urban space and land use patterns has gradually attracted the attention of academia and public policy departments [12-13]. With the increasing demand for automation of storage facilities, the scale of freight facilities (with floor space and building area as basic indicators) has increased significantly in recent years. Facilities with large-area flat roofs (see Figure 2) have a much higher heat capacity and thermal conductivity than most underlying surfaces of buildings and in nature, and have low reflectivity and high absorption of sunlight, resulting in high-temperature environment [14]. The spatial agglomeration of freight facilities further aggravates the heat island effects, which have a negative impact on the physical and mental health of people [15].

Modern freight facilities are large in size. At the same time, due to the large number of vehicle loading and unloading, maintenance, and storage activities, parking lots also occupy a considerable area of land. Low-density development, especially the low-density sprawling pattern that is not subject to systematic planning, has a profound impact on the urban form. The so-called "logistics sprawl" phenomenon

has been discovered in some cities (see Figure 3). Vacant land at low prices and loose development policies have made the suburbs a hot spot for the development of low-density freight facilities [16-17]. Therefore, the area of freight facilities has been continuously increasing in recent years in suburban land in metropolitan areas, where demand is relatively strong. Due to the interdependent relationship of neighboring land uses, the development of other types of land uses in the adjacent areas would be significantly affected [18]. The impact of the inefficiency and disturbance of freight facilities on the development of sustainable urban land use patterns should not be ignored in urban planning and design.

Changes in the construction of freight facilities usually take place on an annual basis, and the corresponding medium-term environmental impacts are gradually intensified along with this change. The impact of this change is imperceptible. When the agglomerated land use forms appear, the irreversible long-term effects will gradually emerge.



a Proportion of various types of car ownership

b Carbon monoxide emission sharing rate

c Nitrogen oxide emission sharing rate

d Particulate emissions sharing rate

Figure 1 Automobile ownership and major transportation air pollutants by vehicle type in China in 2019

Source: Ministry of Ecology and Environment of China

a A logistics facility gathering area in Pudong New Area

b A logistics facility gathering area in Qingpu District

Figure 2 Typical logistics facility clusters in the Shanghai metropolitan area

Source: Bigemap

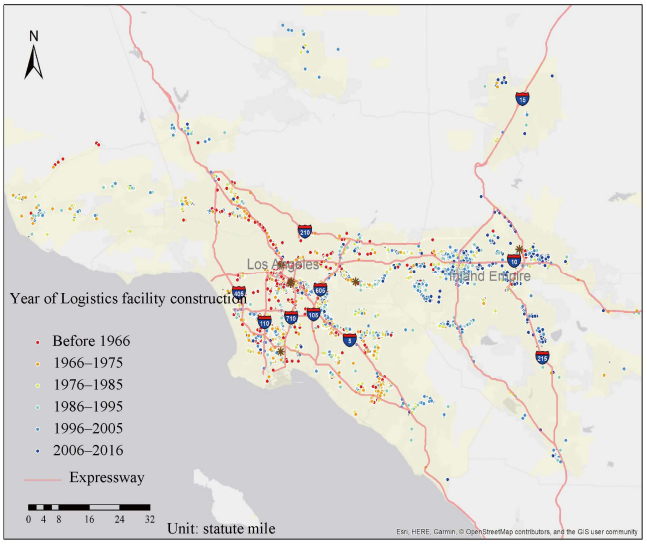


Figure 3 Pattern of logistics sprawl in the Los Angeles metropolitan area in the U.S.

Source: Ref. [3]

1.3 Long-term environmental impact

Comparatively, long-term impacts related to urban land value and socioeconomic structure of population are even more often ignored by urban transportation and environmental policy makers. In the absence of effective standards and regulatory supervision, the generation and agglomeration of negative environmental externalities may cause the depreciation of land value of communities and the imbalance of socioeconomic structure of population in the process of long-term urban spatial change at a decade scale. Negative environmental impacts can reduce the quality of life of surrounding residents, leading to a decline in the demand for surrounding residential units. Simultaneously, changes in land use patterns can decrease the demand for land use types with high added value per unit area (such as commercial land and office). These changes have caused the expected value of the land to continue to shrink.

In recent years, the literature on environmental justice has gradually paid attention to the relevant impact of freight activities. Due to the construction of freight facilities and the agglomeration of freight activities, the flow of population has presented an imbalance trend: the average income level has fallen, the proportion of long-term residents has decreased, and the stability of the community has reduced [18]. These socioeconomic changes, combined with the changes in land value, have seriously affected the improvement and up-gradation of communities.

There is overlap and mixing among the three types of the environmental impact of urban freight activities at different time scales. For example, the emission of air pollutants will cause regional public health problems in the medium and long term [19], and the carbon dioxide emissions of vehicles will cause the greenhouse effect at a longer time scale. The occurrence and effects of such problems are more lasting than the process of emission itself. Therefore, the introduction of the temporal dimension when analyzing the environmental impact of urban freight is not for making an exclusive classification, but for helping policymakers understand the dynamic changes and their mechanisms and more comprehensively evaluate the feasibility and effectiveness of planning and policies.

2 Understanding the environmental impacts of freight from a spatial perspective

The spatial dimension of urban freight environmental impacts is just as important as its temporal dimension. Although the environmental impacts are mainly generated by point features such as vehicles, facilities, and land use parcels, the scope and the way of their influences are often subject to the socio-economic processes at different spatial scales. Policy intervention and guidance cannot be effectively conducted without paying attention to these characteristics.

2.1 Global-scale impact

The occurrence and organization of freight activities in cities are increasingly influenced by global supply chains and value chains. In important metropolitan areas, especially gateway hub metropolitan areas, the entry, processing, transshipment, and distribution of a large number of goods are deeply embedded in the complex and multi-layer global supply chain system (see Figure 5). The means of transportation used by freight in metropolitan areas, the timeliness requirements of transportation and distribution, and the content of freight services may all be managed by multinational companies and platforms participating in global supply chain organizations. Therefore, the spatial structure of the global supply chain is key to understanding the spatial patterns of urban freight-related environmental impacts.

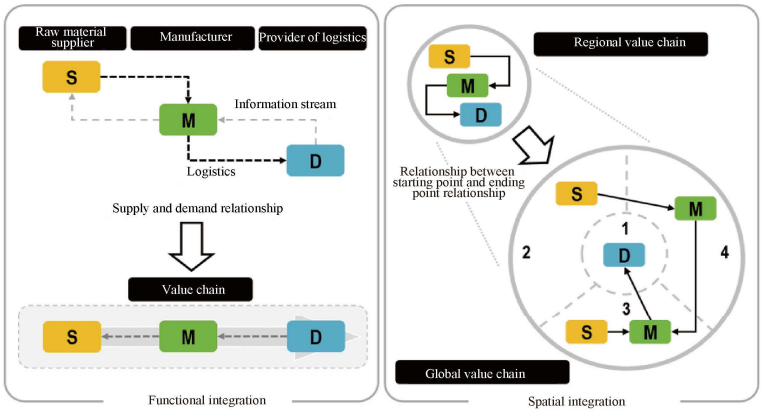


Figure 4 Functional and geographical integration of value chains

Source: Ref. [21]

Let's take Shenzhen, an important gateway city in China, as an example. The scale and intensity of its freight activities have achieved tremendous growth in the past 10 years. In particular, the e-commerce express traffic has increased by 52.5 times from 2007 to 2019. As an important science and technology innovation center in the country and a rising global e-commerce hub, a considerable part of Shenzhen's freight facilities and land use are concentrated in the upstream of the supply chain, that is, the "first kilometer of freight". Simultaneously, driven by cross-border e-commerce, the fast turnover and efficient transfer of goods lead to frequent use of freight vehicles. Such freight demand contributes to the agglomeration of relevant freight environmental impacts.

The globalization trend of the supply chain has led to the fact that local freight activities depend to a large extent on the generation and attraction of freight demand at larger scales. In other words, global supply chains and industrial connections matter in evaluating local activities. When global industrial demand is coupled with local socioeconomic factors, the localized environmental impacts of freight may be inevitable. This structural change calls for the involvement of higher-level authorities, for instance, by formulating regulations and standards at the national and international levels. By analyzing the driving forces of the global supply chain, we can better understand and predict the distribution of local freight activities and the increase or decrease in related environmental impacts, and further assess and control such environmental impacts under the market-government collaboration.

2.2 Regional-scale impact

Part of the environmental impact of urban freight is not limited to the community, but expands and spreads to the whole region through natural and socio-economic processes. The "logistics sprawl" phenomenon mentioned above is widely seen in the metropolitan areas of developed countries. The sprawling expansion of freight land uses can damage the landscape and texture of the suburbs, challenging the balance and integrity of region-wide land use patterns [4, 16]. Affected by the concentrated freight facilities, land use density, floor area ratio, community activity and commercial vitality of the surrounding areas may all experience a significant decline. As a result, the environmental impact of these facilities not only affects local communities, but also extends to the regional scale.

Similarly, although the air pollutants are produced by individual vehicles, they diffuse through atmospheric processes and chemically change with other substances in the air, ultimately affecting the air quality of the entire region. Figure 6 shows the spatial distribution of PM10, an important cargo truck air pollutant, in the Los Angeles metropolitan area. The concentration of this pollutant has a high spatial correlation with freight activities. Due to the complex process of atmospheric flow, the air quality of the entire metropolitan area is affected by the emissions of a large number of freight vehicles across places. This mechanism of impact at the regional scale is very typical.

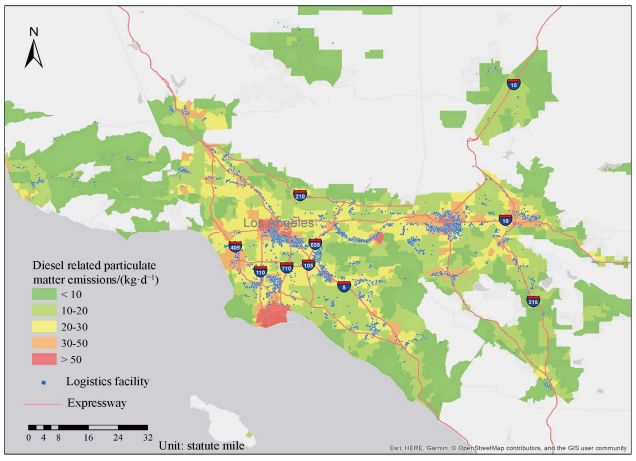


Figure 5 Spatial distribution of diesel related PM emissions and logistics facilities in the Los Angeles metropolitan area

Source: Ref. [3]

Freight linkages are driven by complex and highly localized supply chain requirements. Therefore, the types of freight vehicles and modes of freight transfer vary greatly within heterogeneous regions, and this heterogeneity makes it more necessary to study the impact of freight at the regional scale. For example, given the high activity density and serious congestion in urban central areas or at freight hubs, vehicle emission processes can vary widely across locations, and so do the emission outcomes of certain air pollutants. On the other hand, although the suburban areas have low volume overall traffic, the proportion of freight vehicles among all vehicles is high, and so is the proportion of diesel combustion-related pollutants in all ground traffic air pollutants. In these two scenarios, the way freight vehicles contribute to air pollution varies across urban and suburban contexts, thus leading to the complexity and regionalization of environmental issues.

2.3 Community-scale impact

The community scale is the most intuitive and fundamental scale for understanding and analyzing the environmental impacts of urban freight movement. All enterprises, businesses, and residents in the community are intimate stakeholders regarding the environmental impacts. The coordination and mitigation of conflicts of interest among the stakeholders would depend on the design of conflict management mechanisms at the community scale.

Let's take the noise caused by freight activities as an example. Due to the characteristics of freight demand, especially e-commerce freight demand, a large number of freight vehicles enter and exit freight facilities and hubs 24/7. These vehicle activities result in considerable mechanical noise, which seriously affects the lives of surrounding residents and the operation of commercial facilities. In order to solve this problem, the community can reduce the noise impact to an acceptable level through means such as creating vegetation and structure buffers and setting time windows for vehicle use [22]. Therefore, a community-scale communication and coordination mechanism is the prerequisite for solving this problem. In contrast, higher administrative agencies often have a limited understanding of the scope and extent of the impacts, and it is also difficult to deeply involve them in the process of communication and coordination. In this case, those agencies cannot make fundamental contributions to the solution of the problem.

The environmental impacts of urban freight distribution have attracted growing attention in the field of urban freight in recent years. Road congestion, noise pollution, and hidden traffic safety hazards caused by freight distribution have become chronic problems in many big cities. Therefore, some cities have implemented policies that use communities as the unit of action, such as the "Off-Hour Delivery Program" pilot project in New York City. This plan involves stakeholders in urban distribution activities at the community level. Developing a community interest complex consisting of receiving merchants, freight drivers, shipping companies, and surrounding residents is the key to the success of the plan (see Figure 6). The community complex collects the needs and costs of different parties, offers feedbacks through multi-party meetings and consultations, and seeks action plans that meet the interests of all parties while satisfying the city's sustainable development goals.

3 Evaluation and planning of sustainable urban freight from a compound spatiotemporal perspective

3.1 Evaluation and measurement of environmental impact

The environmental impacts of urban freight activities vary a lot at different spatial and temporal scales. Systematically evaluating and measuring them is a prerequisite for formulating effective and feasible public policies. Existing academic research and public policies mainly focus on the construction and optimization of the urban passenger transportation system, but there is insufficient attention to the freight system that also sustains the urban economic development and people's life. When passenger transportation planning has become a fundamental component of urban planning in most major cities, the formulation and improvement of freight transportation planning appear in only a few cities. In a limited number of existing freight transportation plans, sustainable development has become a popular topic. The assessment and management of the freight-related environmental impacts turn out to be a central focus in those plans.

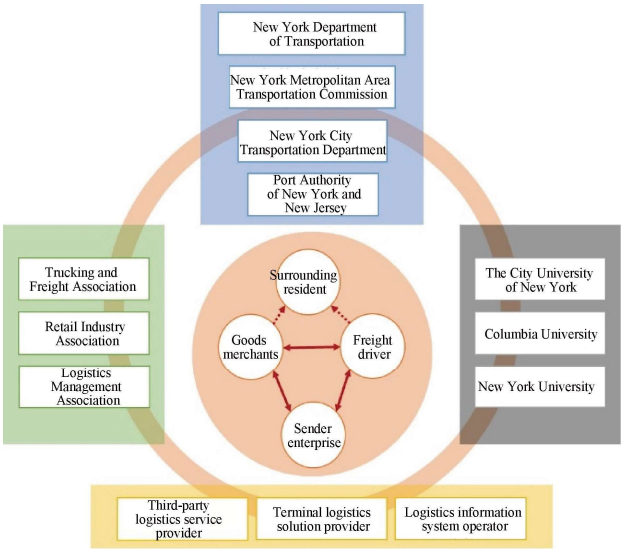


Figure 6 A multi-stakeholder framework of the "off-hour delivery program" in New York, the U.S.A.

Source: Ref. [23]

In 2007, London formulated the *London Freight Plan—Sustainable Freight Distribution A Plan for London* [24], which put forward specific strategies for developing a sustainable freight transportation system. The plan included the history of urban freight development, sustainable development goals, action plans, performance evaluation, multi-party participatory framework, and specific projects and workstreams (see Table 1). Regarding the projects and workstreams, the assessment and research on environmental impacts, including air pollution, carbon emissions, noise and vibration, traffic safety, and negative community impacts were among high-priority goals.

In the formulation of urban freight plans, the spatial and temporal perspectives can help plan makers more comprehensively evaluate the environmental impacts of freight activities. We here propose a few approaches for such consideration. First, according to the spatial characteristics of different environmental impacts, we can determine the spatial scale and the corresponding administrative scope of policy-making, and design a multi-party collaboration framework if necessary. Regional issues may involve multiple levels of government and departments. Second, given the temporal characteristics of different environmental impacts, we can consider the timeliness and cycles of plans, and further determine appropriate short- and long-term planning measures. For example, noise can be controlled by environmental regulations in the short term, but land use requires longer monitoring and guidance. Third, the combination of space-time dimensions has also spawned new planning needs. When congestion and access restrictions are present in urban cores, how to reorganize freight delivery activities in strict space-time windows would become a challenging question to researchers. For complex and dynamic environmental impacts across administrative units, such as traffic congestion, it involves spatiotemporal interactions between a large number of freight vehicles. Therefore, by establishing real-time traffic feedback and cargo matching platforms, the public sector can help improve information exchange and alleviate traffic bottlenecks. Finally, we can take the space-time perspective as the underlying logic of planning reflection. Planning focuses on both forecasting and retrospection. The space-time dimension is among the most important dimensions of social and economic dynamics. By observing the effectiveness of planning measures in the time dimension and the demand changes in the spatial dimension, the pertinence and reliability of planning can be effectively improved, and a more scientific planning plan can be formulated.

3.2 Multi-stakeholder collaboration

As discussed above, the generating mechanism and governance strategy of any form of freight-related environmental impact involve multiple stakeholders, so the sustainable development goals of urban freight systems have to rely on the framework of multi-stakeholder collaboration. By considering the dimensions of time and space, on the one hand, policymakers could enrich and deepen the understanding of relevant mechanisms, especially the behavior patterns and motivations of different stakeholders. On the other hand, it would help design and select action plans that are in line with the interests of each stakeholder, thus ensuring the feasibility and effectiveness of the plan.

Table 1 Assessment of freight planning projects and workstreams in London

Freight planning project and workflow		High-priority Goals						
		Economics			Environment		Society	
		To Support Urban Population and Economic Growth	To Improve the Efficiency of Inter-city Freight Distribution and Service	To Balance Freight Services and Other Transportation Needs	To Reduce Freight Air Pollutants and Carbon Emissions	To Reduce the Impact of Noise and Vibration from Freight	To Reduce freight-related traffic accident casualties	To reduce the negative impact of freight on the community
Project 1	High-quality Freight Carrier Award Program	++	+++	++	+++	++	+++	+++
Project 2	Distribution and Service Planning	+++	++	+++	++	+	++	++
Project 3	Construction freight planning	+++	++	+++	++	+	++	++
Project 4	Freight Information Platform	++	++	+	++	0	+	+
Workflow 1	Multi-party Cooperation and Development	+++	+++	+++	+++	+++	+++	+++
Workflow 2	Data, Modeling and Best Solution Promotion	+	++	+++	++	++	++	++

Note: According to seven evaluation standards (+++, ++, +, 0, -, --, ----), "+++" represents the highest degree of positive impact (Source: Ref. [24])

For instance, the electrification of freight vehicles, which has been frequently discussed in some countries and cities in recent years, is of great significance to the sustainable development of freight movement. However, more and more local practices show that the implementation of the policy should correspond to existing resources and markets, and rely on an action plan that is in line with the long-term interests of different stakeholders. The key factors that affect the policy options include the cost of purchasing and using vehicles by freight companies, the demand of shipping and receiving merchants for the timeliness and reliability of urban deliveries, the investment of the private and public sectors on the construction and maintenance of charging stations, the administrative and financial incentives of the public sector to support the electrification, and the assessment of the environmental performance of electric freight vehicles by different local communities. The effects of these factors vary at different time and space scales. Conditions such as transportation infrastructure, urban form and structure, delivery time windows, and vehicle technical advantages often determine the relative importance of these factors. For example, compared to traditional diesel vehicles, electric freight vehicles may be more suitable for small-volume, high-frequency, and fast-turnover urban delivery in central areas with high population density, widely distributed charging stations, and serious congestion. It is expected to achieve energy efficiency, freight efficiency, environmental (noise) performance, and many other objectives in that specific context. By considering these time and space-related conditions, policymakers could expect better long-term results of the policies.

3.3 People-oriented sustainable development goals

The ultimate goal of developing sustainable urban freight is to improve the quality of the environment and human life. Using the spatiotemporal perspective to measure the freight-related environmental impacts o will help more comprehensively understand the roles and needs of citizens in the urban freight system. The operation and expansion of the freight system have brought much convenience to citizens' daily life by offering time savings and providing opportunities for lifestyle evolution. However, the clustering of freight activities in terms of both time and space, such as the noise by delivery vehicles at night, congestion around freight facilities, and pollution emissions close to seaports all have imposed additional negative effects on certain communities. This imbalance of benefits and costs across places and time periods is deeply embedded in the process of social economy, urban development, and land use expansion. Before the effective intervention of public policies, it is usually difficult for the market to respond with an account of both efficiency and fairness. Therefore, adhering to the people-oriented concept, the public sector might choose to regulate environmental impacts through plans and policies. Understanding the temporal and spatial differences in those impacts is a prerequisite for ensuring that such regulation is accurate and effective.

3.4 Make the best use of big data

Thanks to technological advances such as the Internet and instant messaging, the collection, sharing, and applications of big data on urban freight movement have been widely used, providing a rich source of information for accurately and systematically understanding its activity patterns and characteristics. Research on the environmental impacts of urban freight requires the support of big data, but the methods of data analysis and utilization still need to be enriched and improved. The spatial and temporal dimensions of the impacts can greatly help define big data in the field and broaden the uses of the data. Longitudinal high-resolution satellite images, for instance, can be used to explore the location choices of urban freight enterprises and land uses. With the help of big data analysis, researchers will be able to restore the details of players in the freight system such as vehicles and firms during different temporal processes and at different spatial scales.

4 Conclusions

In today's era of supply chain globalization and e-commerce, sustainable development of urban civilization is highly dependent on the coordination, symbiosis and mutual support of urban systems and freight systems. Only by fully understanding the social benefits and costs of urban freight and evaluating the significance and feasibility of freight planning and policies can we maximize the social values of freight movement. This article proposes a spatiotemporal perspective for studying and exploring the path of urban freight towards long-term sustainability in the contexts with rapid growth in demand, limited environmental space and resources, and multi-stakeholder gaming.

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