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Low-Altitude UAVs and Urban Rail Transit Join Hands to Solve the Last-Mile Problem in Urban Logistics Distribution

-- A Case Study of Tianjin Metro Line 2

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Abstract

Taking Tianjin Metro Line 2 as an example, this paper explores an innovative model for low-altitude UAVs and urban rail transit to collaboratively address the "last-mile" issue in urban terminal logistics distribution. The study proposes the "intelligent rail-UAV collaborative distribution" model, with innovations including: revealing the temporal and spatial complementarity between the "off-peak freight periods" of rail transit and the "point-to-point direct delivery" of UAVs; constructing a network architecture of "suburban distribution center - rail transit station - UAV site - community station"; and designing a joint transportation process: goods are transported to depots (such as Haojixing Logistics Park) via the outer ring road, packaged and then delivered to urban district stations by rail transit, and finally distributed to community stations by UAVs. The temporal-spatial relay model utilizes off-peak hours, non-operating periods, and peak-shifting with passengers to build a three-dimensional network encompassing underground (rail transit), ground (external transportation), and low-altitude (UAVs) layers. For site selection calculation, Tianjin Metro Line 2 is taken as a case, and initial operating stations are determined based on calculated scores, with relevant operational ideas proposed.

Keywords

Low-altitude; Rail Transit; Collaborative Distribution; Last-Mile.

1. Introduction

With the rise of e-commerce express delivery and the logistics industry, the demand for express logistics among Chinese citizens has been steadily increasing. Notably, the demand for daily necessities, primarily consisting of small items, has seen the most significant rise. These goods are characterized by their high degree of heterogeneity, diverse varieties, and small batch sizes, with varying destinations that necessitate dedicated vehicles for transportation. Currently, China's cross-regional transportation has developed relatively maturely, with a variety of transportation modes available, allowing for a cost-effective and efficient balance in cross-regional transportation to achieve optimal solutions. However, with the accelerated pace of urbanization across the country and the rising per capita car ownership, urban roads have become increasingly congested. This situation is particularly dire in densely populated old urban areas. The emergence of urban rail transit has enabled people to bypass congestion, traveling flexibly underground or on elevated tracks with minimal impact from weather and road conditions. Nevertheless, the vast majority of rail transit systems in China are currently operating at a loss, with utilization rates far below expected levels.

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Taking the Jinyidong Rail Transit in Jinhua City (hereinafter referred to as the Jinyidong Line) as an example, its passenger capacity only reaches 40% of its operational capacity, leaving 60% of its capacity idle. Consequently, the Jinyidong Line has adopted freight transportation on its subway. Starting from November 3, 2023, the Jinhua Rail Transit Group, in collaboration with JD Logistics, commenced trial operations of "Jinhua Rail Express," transporting parcels during off-peak hours on the Jinyidong Line. Today, the line carries at least five freight trains daily, delivering parcels to areas along the route such as Jindong District, Yiwu, and Dongyang. In the first quarter of 2024, the freight business on the Jinyi Line generated revenue exceeding 500,000 yuan. This scenario is by no means an isolated case. Effectively utilizing this surplus capacity has become a crucial point for urban rail transit companies to turn losses into profits.

The rapid development of the low-altitude economy seems to offer a solution to this problem. CCID Consulting defines the low-altitude economy as economic activities conducted within low-altitude airspace, primarily utilizing unmanned or manned aircraft as the main transportation mode. It encompasses various operational applications, including passenger and freight transportation, as well as maintenance and inspection, driving the vigorous development of the economy, commerce, and transportation. Ouyang Rihui and others have proposed that the low-altitude economy features a long industrial chain, a wide radiation range, diverse market entities, and technical-economic characteristics such as innovation-driven, space-dependent, cross-border integration, and radiation-driven effects[1]. Chi Xiaoyu utilized SWOT analysis to explore the feasibility of joint vehicle and drone delivery to address the challenge of the "last mile" in rural areas[2]. Feng Dikun and others proposed a multi-level unmanned aerial vehicle station site selection for cities, studying the collaborative planning of multi-level takeoff and landing site networks for drone logistics in urban environments[3]. Adam Motraghi and others developed an event-based simulation model using ARENA to consolidate the advantages of urban rail freight and demonstrate its viability as a feasible alternative to the most popular methods in today's freight market[4]. Alex Dampier and others used software provided by the transportation department to simulate urban subway freight, showing that implementing this plan would save a significant number of accidents, reduce casualties on the roads, and save funds due to the decreased injury rate, concluding that the plan is feasible[5]. Feng Jianghong and others analyzed the feasibility and practical research of existing M-ULS projects at home and abroad, indicating that China currently possesses the policy, regulatory, market environment, and technological means to carry out subway freight operations[6]. Song Minhua and others proposed that low-altitude transportation will open up new tracks and cultivate new business formats for the urban rail industry, bringing historical opportunities for expanding development space and enhancing internal driving forces[7]. These studies provide a theoretical foundation for this paper.

Currently, there are numerous studies on the development of the low-altitude economy across various industries. However, research on the collaborative delivery of drones and rail transit for completing the "last mile" of urban distribution is scarce. Against this backdrop, this paper proposes an innovative model of "Smart Rail Transit-Drone Collaborative Delivery," revealing the spatiotemporal complementarity between the "off-peak freight periods" of urban rail transit and the "point-to-point direct delivery" of drones. It proposes a four-level network architecture of "suburban distribution center-rail transit station-drone station-community depot," aiming to build a green and environmentally friendly new form of last-mile logistics distribution.

2. Concept and Feasibility Study

Currently, most economically developed cities in China have opened urban rail transit networks. Connecting various functional areas and groups of the city, they assume the task of commuter transportation with their advantages of high speed and large capacity. UAVs, on the other hand, have the characteristics of low manufacturing and maintenance costs, flexible transportation, and little interference from terrain, which can form a good complementary advantage with urban rail transit.

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Moreover, metro depots are generally located near the starting and ending stations of the lines. These stations are often situated in the suburban areas of the city, with wide roads and low traffic volume, and are usually surrounded by large logistics hubs or industrial parks, making them suitable for forming cargo distribution centers. Taking Tianjin Metro as an example, the following table 1 lists the distribution around the starting and ending stations of some Tianjin Metro lines:

Table 1. Distribution of Logistics Facilities Around Tianjin Metro Depots

Line	Depot Distribution	Surrounding Facilities
Line 1	Liuyuan Depot	Haojixing Logistics Park
Line 2	Caozhuang Depot	Tianjin Logistics and Freight Center
Line 2	Limingzhuang Depot	JD.com Asia No.1 Tianjin Intelligent Logistics Park, Airport Economic Zone
Line 5	Shuangjie Depot	Tianjin Beichen Suning Cloud Warehouse
Line 6	Dabi Zhuang Depot	Tianjin Quancheng Logistics Distribution Co., Ltd., JD.com Phase II Logistics Park
Line 7	Dasi Depot	Saida Industrial Park

After arriving in Tianjin, goods can first be sorted to determine the target district and the corresponding metro line. They are then transported to the depot of the selected line via the outer ring road, packaged according to different stations, and loaded uniformly. Subsequently, they are transported to the station in the target urban district by rail transit and delivered by UAVs waiting at the station, realizing the joint transportation of low-altitude UAVs and urban rail transit.

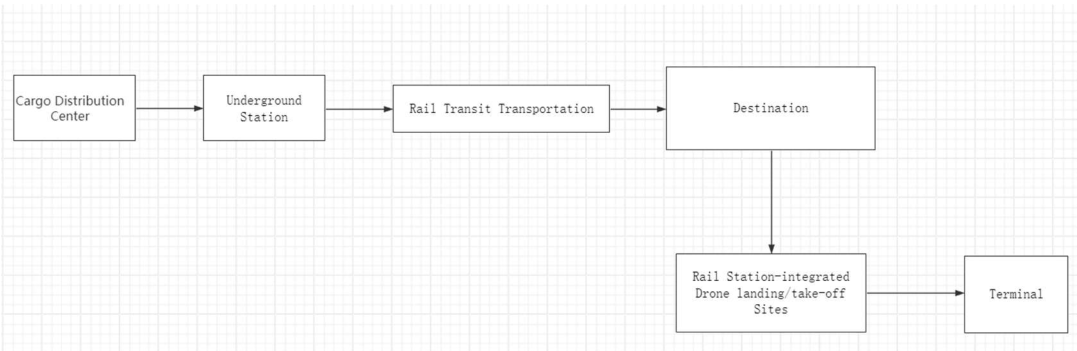

Figure 1. Distribution Schematic Diagram

In terms of time, we can utilize the off-peak hours of the lines, as well as the periods after passenger operation ends and non-maintenance windows (line maintenance and inspection) for transportation. This achieves "peak-shifting" with passengers while effectively utilizing the remaining transportation capacity of the metro network, thereby forming a temporal-spatial relay operation model of "underground night trunk transportation + low-altitude daytime terminal delivery"[8-10]. Meanwhile, Metros Line 4, 5, and 6 have reserved space for 8-car and 7-car Type B trains. We can fully utilize these reserved spaces by adding modular freight carriages to expand their transportation capacity, making them the main underground transportation lines.

In terms of space, urban cargo transportation is divided into three layers: the underground layer, the ground layer, and the low-altitude layer. The underground layer mainly consists of the transportation of underground rail transit connecting cargo distribution centers and stations in various groups in the

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city. The ground layer refers to the transportation from external areas to the depots in suburban or exurban areas. The low-altitude layer involves UAVs distributing goods from stations to various communities and even individual households, thereby constructing a three-dimensional urban cargo distribution network.

For goods sorting, RFID (Radio Frequency Identification) technology can be used to screen the metro line for each item and conduct classified packaging, which can be implemented with the following code (C language). (Note: The Luxian Section of Line 6 is Line 8)

```
#include <stdio.h>
#include <string.h>
typedef struct {
    int line_number;
    char stations[50][50]; // Maximum 50 stations per line
    int station_count;
} MetroLine;
int main() {
    // Initialize data for 11 metro lines
    MetroLine lines[11] = {
        {1, {"A1", "B1", "C1", "D1", "E1"}, 5},
        {2, {"A2", "B2", "C2", "D2", "E2"}, 5},
        {3, {"A3", "B3", "C3", "D3", "E3"}, 5},
        {4, {"A4", "B4", "C4", "D4", "E4"}, 5},
        {5, {"A5", "B5", "C5", "D5", "E5"}, 5},
        {6, {"A6", "B6", "C6", "D6", "E6"}, 5},
        {7, {"A7", "B7", "C7", "D7", "E7"}, 5},
        {8, {"A8", "B8", "C8", "D8", "E8"}, 5},
        {9, {"A9", "B9", "C9", "D9", "E9"}, 5},
        {10, {"A10", "B10", "C10", "D10", "E10"}, 5},
        {11, {"A11", "B11", "C11", "D11", "E11"}, 5}
    };
    char destination[50];
    printf("Please enter the goods destination: ");
    scanf("%49s", destination);
    int found = 0;
    for (int i = 0; i < 11; i++) {
        MetroLine *line = &lines[i];
        for (int j = 0; j < line->station_count; j++) {
            if (strcmp(destination, line->stations[j]) == 0) {
                printf(""The destination belongs to Line %d, Station %s\n", line->line_number,
line->stations[j]);
                found = 1;
                break;
            }
        }
```

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```
        if (found) break;
    }
    if (!found) {
        printf("ERROR\n");
    }
return 0;
}
```

Therefore, by constructing a three-dimensional transportation corridor (underground, ground, and air), we can break through the physical limitations of traditional planar road networks and realize the three-dimensional utilization of urban spatial resources.

3. Operational Ideas

This scheme is applicable to small goods with small volume and weight, which are placed in carts for transportation without affecting passengers' travel experience. Currently, urban logistics distribution centers in China are located in suburban areas with low traffic volume. After sorting, goods can be transported by vehicles to rail transit stations, then delivered to corresponding stations by trains, unloaded by staff, transported to UAV sites, and finally delivered to corresponding community stations by UAVs.

4. Site Selection Calculation

Taking Tianjin Metro Line 2 as an example, the line starts from Binhai International Airport Station in the east and ends at Caozhuang Station in the west, passing through Dongli District, Hedong District, Hebei District, Nankai District, and Xiqing District. It has 20 stations in total, with two depots: Limingzhuang Depot and Caozhuang Depot. As a core east-west trunk line in Tianjin, the Caozhuang Depot is adjacent to the Tianjin Logistics Center, and the Limingzhuang Depot is close to the Airport Economic Zone, both of which are excellent logistics transportation nodes. Except for Binhai International Airport Station, the other 19 stations of the line are evaluated and scored to determine the optimal site selection.

The influencing factors set are: X1: Number of residential areas around the station (within a 2-kilometer radius); X2: Approximate UAV delivery distance (cost); X3: Station accessibility (number of transfer lines).

The scoring method proposed by expert Zeng Xianke from CNKI (China National Knowledge Infrastructure) was adopted to evaluate each station, with weights of 0.25 for X1, 0.33 for X2, and 0.42 for X3 [11].

The calculation formula is as follows:

First, normalize each item of data using the following formula:

$$X_{1i}=\frac{x_{1i}}{\sum_{i=1}^{n} x_{1i}} \tag{1}$$

$$X_{2i}=\frac{x_{2i}}{\sum_{i=1}^{n} x_{2i}} \tag{2}$$

$$X_{3i}=\frac{x_{3i}}{\sum_{i=1}^{n} x_{3i}} \tag{3}$$

Then, calculate the total score based on the expert-assigned weights:

$$P_i=X_{1i}\times 0.25+X_{2i}\times 0.33+X_{3i}\times 0.42 \tag{4}$$

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The resulting data are as follows (Table 2):

Table 2. Station Scoring Table for Tianjin Metro Line 2

Station Name	Comprehensive Score	Station Name	Comprehensive Score	Station Name	Comprehensive Score
Airport Economic Zone	0.0198510224909293	Ocean International Center	0.0341092605649329	Changhong Park	0.0972352425718233
Guoshan Road	0.0202786121390826	Tianjin Railway Station	0.156994830888358	Xianyang Road	0.0311710566903312
Dengzhou Road	0.0241118393404661	Jianguo Road Italian Style Town	0.0377713836361131	Jieyuan West Road	0.0270528893678154
Yudongcheng	0.0839121430398493	Southeast Corner	0.0398581584212917	Bianxing	0.0239629034834486
Cuifu New Village	0.0281784121460423	Gulou	0.0984222105209998	Caozhuang	0.01939206628783
Jingjiang Road	0.092162529891775	Southwest Corner	0.0965021980314343		
Shunchi Bridge	0.0336001915035434	Guangkai Fourth Road	0.0354330490108374		

Among them, Tianjin Railway Station ranks first with a score of 0.1570, and the detailed ranking is as follows (Table 3):

Table 3. Station Scoring Table for Tianjin Metro Line 2 (Sorted)

Station Name	Comprehensive Score
Tianjin Railway Station	0.156994831
Gulou	0.098422211
Changhong Park	0.097235243
Southwest Corner	0.096502198
Jingjiang Road	0.09216253
Yudongcheng	0.083912143
Southeast Corner	0.039858158
Jianguo Road Italian Style Town	0.037771384
Guangkai Fourth Road	0.035433049
Ocean International Center	0.034109261
Shunchi Bridge	0.033600192
Xianyang Road	0.031171057
Cuifu New Village	0.028178412
Jieyuan West Road	0.027052889
Dengzhou Road	0.024111839
Bianxing	0.023962903
Guoshan Road	0.020278612
Airport Economic Zone	0.019851022
Caozhuang	0.019392066

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Therefore, in the initial stage of the collaborative distribution operation between UAVs and urban rail transit, the following stations should be selected as UAV takeoff and landing sites: "Tianjin Railway Station", "Gulou Station", "Changhong Park Station", "Jingjiang Road Station", and "Yudongcheng Station". Similar to metro station selection, these stations are designated as "anchor stations", and the remaining stations as "dissociate stations".

Anchor stations refer to stations that must be determined and set first in the initial planning stage.

Dissociate stations are set based on other influencing factors after the determination of anchor stations.

Since "Southwest Corner Station" and "Southeast Corner Station" are close to several other "anchor stations" with overlapping coverage areas, they are also regarded as "dissociate stations". In the mid-term operation stage, based on the 2-kilometer coverage standard, stations should be grouped in pairs, and the station with the higher score in each pair should be selected as the UAV takeoff and landing site (i.e., "anchor station"), while the other as the "dissociate station". At this stage, the selected stations are: "Guoshan Road Station", "Yudongcheng Station", "Jingjiang Road Station", "Ocean International Center Station", "Tianjin Railway Station", "Gulou Station", "Southwest Corner Station", "Changhong Park Station", and "Jieyuan West Road Station". In the later operation stage, with the increase in express delivery demand, takeoff and landing sites can be set up at all stations of the line, forming an efficient and convenient low-altitude terminal distribution network, which effectively alleviates the last-mile distribution problem in the city.

5. Future Outlook

With the socio-economic development and technological progress in China, the research and development of the low-altitude economy will gradually improve. The development of the low-altitude economy has effectively utilized the airspace between the ground layer and the current civil aviation transportation airspace, giving full play to the point-to-point transportation advantages of aircraft. Meanwhile, as China's urbanization process accelerates, the metro networks of various cities are gradually taking shape and improving. With the increasing difficulty in obtaining approval for new metro projects, the metro networks of most cities have basically been finalized, so the current planning will not undergo significant changes in the later stage. Therefore, utilizing the large transportation capacity of metro and the flexible distribution of UAVs to build a three-dimensional integrated urban transportation network will effectively alleviate the last-mile problem in terminal distribution, providing a new solution to urban terminal distribution and traffic congestion issues.

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