Integration of UAVs with public transit for delivery: Quantifying system benefits and policy implications

Citation for the original published paper (version of record):

Cui, S., Yang, Y., Gao, K. et al (2024). Integration of UAVs with public transit for delivery: Quantifying system benefits and policy implications. Transportation Research Part A: General, 183. http://dx.doi.org/10.1016/j.tra.2024.104048

N.B. When citing this work, cite the original published paper.

(article starts on next page)

Transportation Research Part A 183 (2024) 104048

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Integration of UAVs with public transit for delivery: Quantifying system benefits and policy implications

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ARTICLE INFO

Keywords:
Unmanned aerial vehicles
Public transportation
Mode integration
Public transit revenue
System benefits

ABSTRACT

The maturation and scalability of unmanned aerial vehicle (UAV) technology offer transformative opportunities to revolutionize prompt delivery. This study explores integrating UAVs with public transportation vehicles (PTVs) to establish a novel delivery paradigm that enhances revenue for public transit operators and improves transport system efficiency without compromising passenger convenience or operational efficiency. Employing hexagonal planning technology, this study identifies and quantifies the available spatio-temporal resources of PTVs for UAV integration. This involves aligning the spatio-temporal dynamics of prompt delivery orders with PTV ridership, based on field data from Beijing's Haidian District. Utilizing these outputs, we quantitatively analyze the benefits of integrating UAVs with PTVs on increasing public transit revenue, and potentials of reducing carbon emissions and mitigating congestion. Furthermore, we quantify the long-term benefits of UAV-PTV integration by predicting future increases in delivery demand. Based on obtained quantitative results, this study discusses practical and policy implications to support the sustainable integration of UAVs with PTVs.

1. Introduction

As an integral component of social welfare, public transport systems offer essential mobility services to all residents, even though some routes have very low ridership (see Fig. 1). In most cities, public transit systems require financial subsidies from urban authorities due to the high costs of capital infrastructure and operation (He et al., 2022; Ji et al., 2022). Consequently, numerous cities are investigating innovative operational approaches for public transit systems to enhance fiscal revenue, fostering sustainable development (Zhong et al., 2023; Zeng and Qu, 2023; Li et al., 2024). Utilizing existing public transport infrastructure during off-peak hours or idle periods for commercial purposes offers transit operators opportunities to increase revenue without impacting their primary function of facilitating passenger travels (Cheng et al., 2023; Cavallaro and Nocera, 2023; Kellermann et al., 2020; Li et al., 2022b; Wang et al., 2023). Reports indicate that Beijing Subway used the available capacity of three rail transit lines (i.e., Line 9, Fangshan Line, and Yanfang Line) during off-peak hours for intra-city express delivery in 2023. This strategy potentially improves public transit operators' revenue, thereby alleviating financial burdens.

Integrating unmanned aerial vehicles (UAVs) with public transportation vehicles (PTVs) for prompt delivery emerges as a strategically compelling approach to utilize the capacity of PTVs. This strategy involves two key components. Firstly, PTVs carry UAVs for long-distance travel between stops and leverage their available space for goods transport during off-peak hours. Secondly,

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https://doi.org/10.1016/j.tra.2024.104048

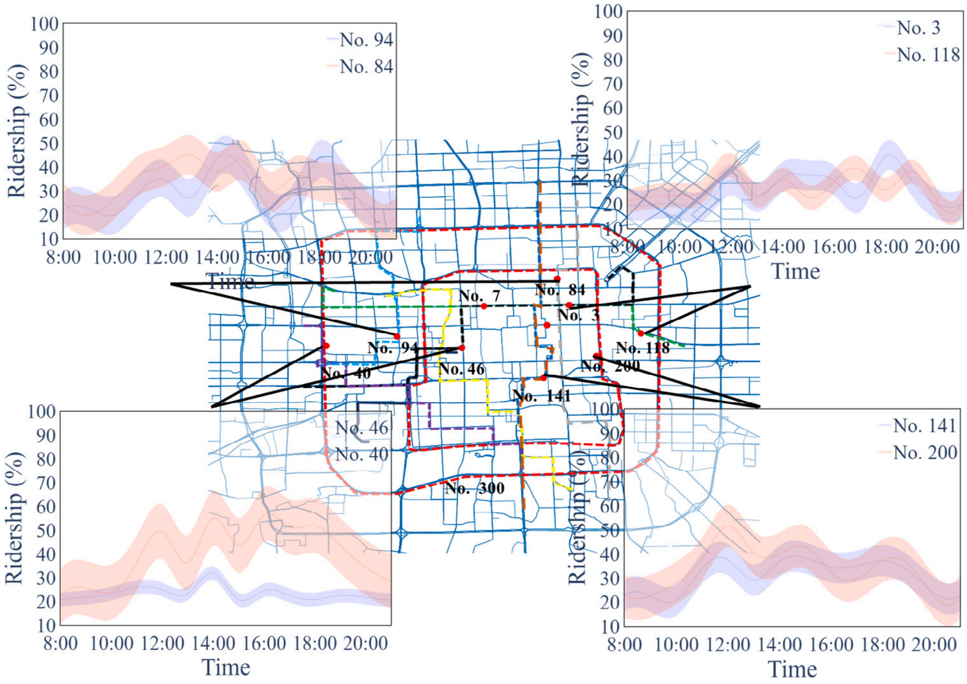

Fig. 1. Bus routes with low ridership in Beijing, China.[1]
Source: Amap (2023).

UAVs independently conduct first and last mile deliveries from the public transit stations. Utilizing UAVs for last-mile deliveries offers significant potential benefits, including increased income for public transit operators, reduced traffic congestion (owing to fewer logistic vehicles in urban areas), lower exhaust emissions, and diminished infrastructure maintenance costs (Baldisseri et al., 2022; Garg et al., 2023; Machado et al., 2023; Zhu et al., 2023). These potential advantages highlight the importance and necessity of conducting a quantitative investigation into the effects of integration of UAVs with PTVs based on data.

Narrow urban streets, limited parking, and restricted access present formidable obstacles for vehicle-based last-mile delivery, worsening traffic congestion in metropolitan areas (Cui et al., 2024; Fotouhi and Miller-Hooks, 2023; Feng et al., 2023; Xu et al., 2023; Gao et al., 2023). Recently, there has been an exponential rise in the adoption of UAVs across various domains, especially in logistics (Chung, 2021; Hossain et al., 2022; Lewis et al., 2021; Rai et al., 2022; Rejeb et al., 2023). Research has highlighted the adaptability of UAVs, particularly underscoring their efficiency and maneuverability in urban terrain Paddeu and Parkhurst (2020), She and Ouyang (2021). Many research and commercial efforts by industrial giants, including Amazon, DHL, Google, United Parcel Service (UPS), JD Logistics, and SF Express, have been conducted to utilize UAVs for delivery purposes (Lin et al., 2022). Specifically, Amazon Prime Air plans to deploy UAVs for dispatching compact express parcels, promising delivery of items weighing less than 5 pounds within 30 min after order confirmation (Mohammad et al., 2023). Similarly, DHL has tested UAV-based last-mile deliveries in urban areas in China, reducing the one-way delivery duration from 40 min to 8 min (DHL, 2019). The increasing utilization of UAVs indicates a pivotal shift towards aerial solutions in delivery dynamics, potentially enhancing the efficiency of urban logistics.

However, using UAVs for city-wide logistics also presents significant challenges that require attention (Dayarian et al., 2020; Li et al., 2022a; Outay et al., 2020; Perboli and Rosano, 2019). UAVs are vulnerable to potential security attacks, including cyber attacks and unauthorized access, posing significant challenges to their deployment in certain urban areas (Cui et al., 2023; Feng et al., 2021; Xue et al., 2024a,b). While UAVs are adept at dispatching small parcels over short distances, their payload capacity and range limitations make them unsuitable for long-distance logistical operations (Chen et al., 2022; Chiang et al., 2019; Doole et al., 2020). Therefore, some research is directed towards the vehicle routing challenges about dispatching UAVs in limited spaces (Roberti and Ruthmair, 2021; Simoni et al., 2020). Addressing last-mile logistics, Lin et al. (2022) and Yurek and Ozmutle (2018) delved into the traveling salesman problem for UAVs. Their studies investigated the optimization of UAVs schedules in the context of new clients and the constraints posed by cargo delivery timelines. Zhang et al. (2021) explored the simultaneous forward and reverse logistics vehicle routing problems within given time windows, where both pick-up and delivery time windows were considered simultaneously. Furthermore, it is critical for municipal administrations and transport managers to develop comprehensive regulations and protocols

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[1] In the bus ridership figures, bold solid lines represent the mean bus ridership for the specified time interval. Concurrently, the boundaries of the shaded areas denote the upper and lower quartiles of bus ridership.

to facilitate the smooth integration of UAVs into urban logistical operations. This framework must address key aspects, such as airspace governance, noise pollution, and potential secondary impacts on the existing transit infrastructure.

Considering the noted safety, efficiency, and policy challenges in UAV applications, integrating UAVs with other transportation modes emerges as a potentially beneficial strategy for urban logistics (Barmpounakis and Geroliminis, 2020; Elsayed and Mohamed, 2020; Lemardelé et al., 2021). JD Logistics has introduced a UAV-truck logistics delivery system (Sun et al., 2021). Trucks, capable of transporting significant cargo volumes, are equipped with large-capacity batteries, allowing them to function as mobile charging stations for UAVs. This hybrid UAV-truck strategy manages to fulfill 25% of daily orders while cutting the delivery time in half. However, widespread road congestion has resulted in notable delays in UAV-truck logistics, especially the delays of trucks (Gonzalez-R et al., 2020; Ham, 2018; Murray and Chu, 2015). Conducting deliveries during off-peak times such as nighttime, can enhance delivery efficiency by 3%–30% (Cortes and Suzuki, 2022). In addition to UAV-truck integration, other research has explored integrating PTVs with UAVs, using the inherent consistency of PTV operations due to their structured routes, schedules, and, in some instances, dedicated lanes. Huang and Savkin (2023) introduced a UAV-PTV integration based approach to urban aerial surveillance where UAVs are positioned atop PTVs. They constructed a mixed-integer programming model to allocate UAV surveillance tasks, aiming to reduce energy consumption and ensure UAVs' safe return. Their model accommodated fixed time windows for urban surveillance to maintain timeliness. Their hypothesis was based on UAVs being positioned atop PTVs. Consequently, they did not align the spatiotemporal dynamics of logistics orders with PTV ridership.

Integrating UAVs with PTVs emerges as a promising solution for prompt delivery challenges. PTVs, serving as extensive public passenger transport, are spatially well-distributed in urban areas. UAVs can complement this PTV-centric transportation by providing swift, direct, and adaptable connections to end recipients. The expected benefits include decreased congestion, shortened delivery times, and improved accessibility. However, integrating UAVs into existing public transportation infrastructure presents complexities, particularly in coordinating public transit timetables and network structures with the spatio-temporal dynamics of delivery orders. Considering the efficacy and complexity of the aforementioned UAV-PTV integration, this study evaluates its impact on public transport revenue, traffic efficiency, and emissions. This research contributes to the field are as follows.

(1) This study identifies and quantifies the available spatio-temporal resources of PTVs using hexagonal planning technology and aligning them with the dynamics of prompt delivery orders and PTV ridership for UAV integration for delivery.

(2) This study evaluates the necessary time tolerance threshold of recipients for the effective integration of PTVs and UAVs, ensuring the comprehensive fulfillment of prompt delivery orders.

(3) This research forecasts prompt delivery orders in the future and evaluates potential revenue benefits for PTV operators from PTV-UAV integration.

(4) The study quantitatively estimates the reduction in carbon emissions and the alleviation of traffic congestion resulting from the PTV-UAV integration.

The structure of this paper is as follows. Section 2 provides a comprehensive description of PTV-UAV integration in addressing prompt delivery challenges. In Section 3, we investigate the spatiotemporal characteristics of prompt delivery orders. In Section 4, we explore the spatiotemporal dynamics of PTV ridership, applying hexagonal planning techniques to align these dynamics with delivery orders. Section 5 conducts a statistical analysis of recipients' time-tolerance thresholds, evaluates the increased operational revenue, and investigates the potential reduction in traffic congestion and emissions from PTV-UAV integration. Finally, Section 6 presents conclusions with discussions.

2. Problem description

This study investigates the potential of integrating UAVs with PTVs to improve the revenue of PTV operators and simultaneously mitigate traffic congestion and emissions (Fig. 2). PTVs herein include buses, trains, and trams. UAVs are able to ride on PTVs and be transported as "passengers". The maneuverability of UAVs enables them to move fast in compact and dense urban areas compared to vehicles, thus facilitating efficient door-to-door package collection and last-mile delivery. After collecting packages, UAVs chooses the optimal PTV stops and PTVs to ride based on planned routes and timetables and rideship of PTVs. After reaching the intended stations of a PTV route, UAVs can get off or move to another PTV, using their flexibility to complete the last-mile delivery smoothly. While PTV routes might seem more indirect and time-consuming than direct private vehicle delivery, UAVs are adept at quick and often direct delivery for the last mile, effectively bypassing traffic bottlenecks. The 'last mile' generally is the most time consuming and least efficient phase of a whole delivery process, particularly in congested urban areas. Hence, the integration of PTVs and UAVs may present advantage for prompt last-mile delivery by reducing the reliance on private vehicle. We aim to quantify the potential increase in PTV revenues that could result from this integration of UAVs from delivery, depending on an acceptable time tolerance threshold. Meanwhile, we also evaluates the time tolerance threshold of recipients within this integrated framework. Reducing the mileage of delivery vehicles from integration of PTVs with UAVs can lower their environmental impact and improve traffic efficiency. Therefore, we also quantitatively evaluates the potential for reduced emissions and improved traffic efficiency resulting from integration of PTVs with UAVs.

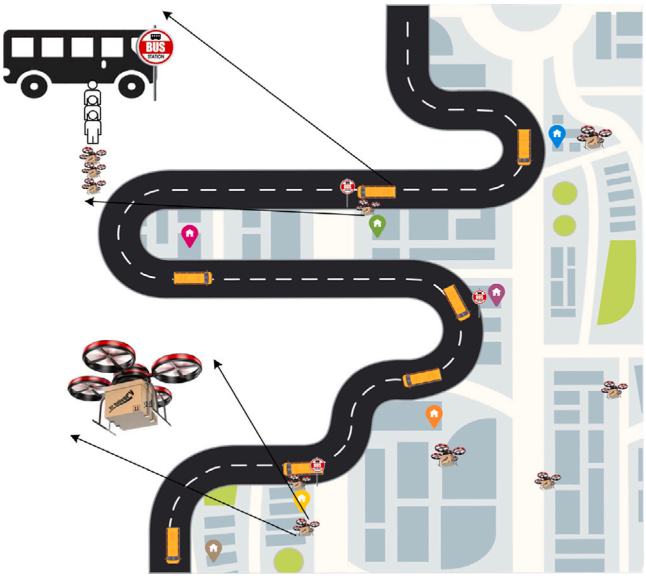


Fig. 2. Problem description of PTV-UAV integration for prompt delivery.
Source: Tree Top International School (2023) and Tujingling (2023).

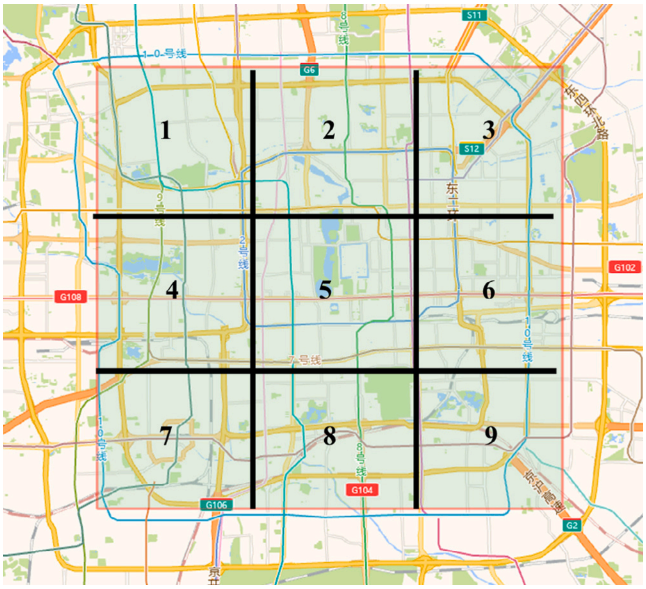


Fig. 3. Regional division.

3. Spatiotemporal characteristics of prompt delivery orders

To thorough examine the potential of UAV-PTV integration, it is essential to analyze the spatiotemporal characteristics of prompt delivery orders. The spatiotemporal characteristics is crucial to determine the match-up between prompt delivery orders and scheduled timetables and routes of PTVs, which is the foundation of UAV-PTV integration. Data on prompt delivery orders in Beijing's Haidian District released by Didi Chuxing, covering a three-week period from November 29 to December 18, 2016, are utilized for our analysis. This study area covers the area defined by longitudes 116.30 to 116.47 and latitudes 39.85 to 39.97 (see Fig. 3). To improve the accuracy of investigating the spatiotemporal match-up between the time and locations of prompt delivery orders and PTV (timetables and routes), the study area is further divided into nine smaller subareas, illustrated in Fig. 3.

Fig. 4 illustrates the statistics of prompt delivery orders in the three-week period, delineated at hourly intervals. Most of the prompt delivery orders are within standard working hours (i.e. 9 am to 5 pm) and not during the morning or evening rush hours.

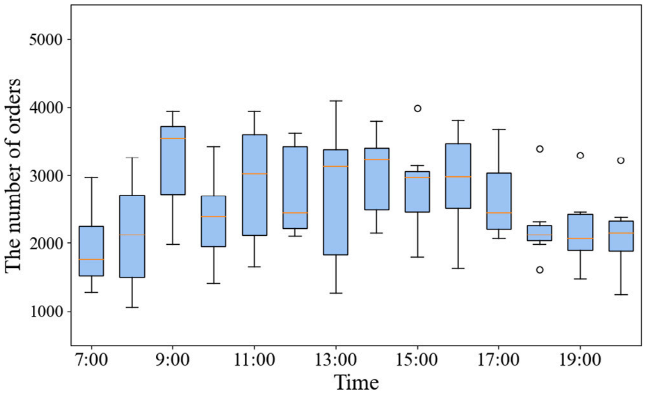


Fig. 4. Timing characteristics of prompt delivery orders.

This implies that prompt delivery packages are unlikely to affect the constrained passenger capacity of PTVs during peak hours. Considering that PTV ridership typically decreases out of peak hours, accommodating a substantial number of UAVs on PTVs is unlikely to adversely affect passenger satisfaction. Furthermore, during non-operational hours of PTVs (i.e. 10 pm to 6 am in the next day), prompt delivery orders make up approximately 10% of all orders. Currently, this proportion of prompt delivery orders during PTV non-peak hours does not justify the extension of PTV operational schedules for PTV-UAV integration. However, if the volume of prompt delivery orders increases, there may be a potential motivation for PTVs to expand their operational hours, potentially increasing revenue streams and enhancing urban mobility by leveraging vacant time of PTVs. However, during PTV non-peak hours when roads are not congested, the time required by an integrated PTV-UAV system to complete prompt deliveries is significantly longer than that for private vehicles, necessitating a higher time tolerance threshold from recipients for prompt delivery.

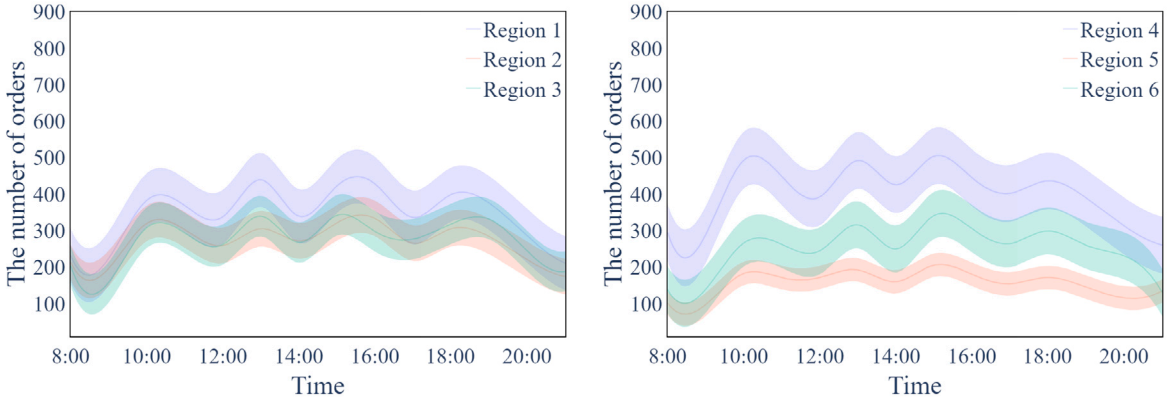
Figs. 5 and 6 show the statistical features of prompt delivery orders in each subarea as the origin and destination of delivery orders, respectively, delineated by hourly intervals. In each figure, the upper and lower boundaries of shaded regions represent the upper and lower quartiles of orders, respectively. Comparative analysis of Figs. 4, 5, and 6 shows that the temporal statistical characteristics of prompt delivery orders in individual regions closely reflect the aggregate order statistics in Fig. 4. Most of these orders in each region are during standard working hours (i.e. 9 am to 5 pm), not in the morning and evening peak operational hours of PTVs. Therefore, UAVs can be potentially utilized to use the non-peak hours of PTVs in each region for prompt delivery, potentially yielding additional revenue while also reducing traffic congestion and emissions due to private vehicle deliveries.

Fig. 7 shows the spatial patterns of origin–destination pairs of prompt delivery orders, based on the average number of prompt delivery orders per hour from each of these periods. The number of prompt delivery orders in the off-period (see Fig. 7(b)) is higher than that in the morning peak period (see Fig. 7(a)) and in the evening peak period (see Fig. 7(c)). This trend is opposite to the bus rideship. Therefore, using PTV-UAV integration to solve prompt delivery will not cause passenger dissatisfaction and reduce the number of passengers. The x-axis and y-axis denotes the origins and the destinations, respectively, and red color indicates higher order volumes. Results for morning peak, evening peak, and off-peak times are displayed separately. In the morning peak, there is a clear gathering of orders starting from region 3 and heading to region 6. Conversely, the evening peak shows a more spread out distribution of orders with significant clusters between regions 2 and 7, and regions 5 and 6. The off-peak period shows a reduced number of prompt delivery orders, mainly focused in regions 4 and 7. The data indicates a significant correlation between order amount and time periods for specific regions. For instance, orders from region 4 to region 7 and from region 1 to region 4 see a sharp increase during the morning rush hour, while in the evening peak period, the delivery direction reverses.

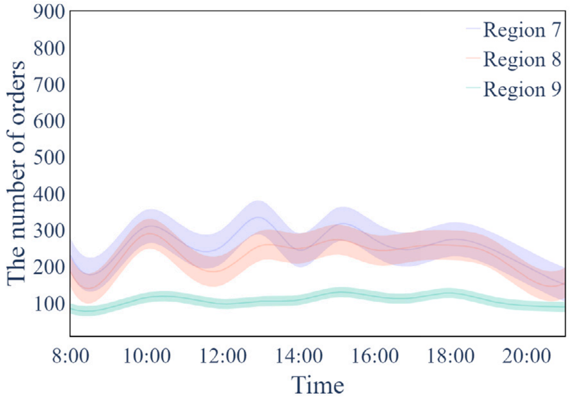
4. PTV route filtering and matching

Owing to constraints such as air traffic control regulations and limited battery capacity, UAVs are generally restricted to operating within specific areas and a limited range. We further divides the study area into smaller zones that fit the service area of UAV in PTV-UAV integration for prompt delivery, employing hexagonal planning techniques (Fig. 8). Hexagonal planning provides an advantage in reducing sampling biases due to edge effects commonly found in grid-shaped layouts. Nine bus routes shown in Fig. 8 are selected for analysis to guarantee that each hexagonal area has at least one bus stop for PTV-UAV integration. Details about the bus routes, including starting and ending locations, frequency, route lengths, and first and last departure times, are summarized in Table 1. It is worth noting that the total number of bus routes in the study region is more than the selected ones. These nine routes are chosen due to their nearly uniform distribution across the region.

In evaluating the feasibility of integrating PTVs with UAVs for prompt delivery, this study analyzes the ridership data of the selected nine bus routes from September 11 to September 17, 2023. Fig. 9 illustrates the ridership for each bus route, with bold curves indicating the average value and the upper and lower boundaries of shaded areas denoting the upper and lower quartiles. The figure indicates that the mean ridership is close to the upper and lower quartiles and does not have large weekly ridership fluctuations. Moreover, Fig. 9 reveals that most bus routes maintain a ridership of approximately 50%, even during peak morning and evening hours. This finding highlights the underutilization of buses as a societal resource. Therefore, UAVs carrying packages could potentially utilize bus vacant space for prompt delivery, potentially without compromising passenger service satisfaction.



(a) Regions 1 to 3 (b) Regions 4 to 6



(c) Regions 7 to 9

Fig. 5. Spatiotemporal characteristics of prompt delivery origins.

Table 1
Bus line information.

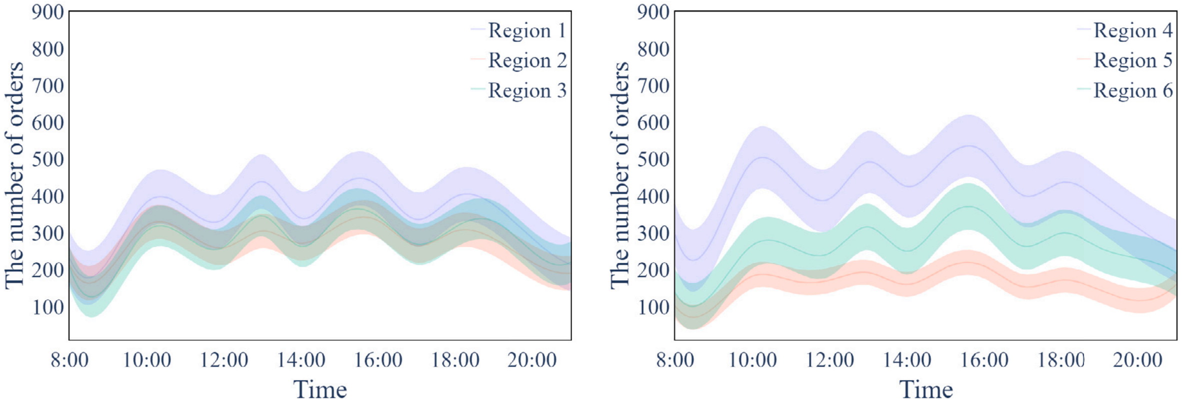
Lines	Start points	End points	Line length	Off-Peak/Peak departure intervals	First/Last departure times
No. 300	Heping East Bridge	Heping East Bridge	48 km	12 min/7 min	5:30/22:00
No. 118	Hongmiao Road Dong	Zizhuyuannan	17 km	16 min/9 min	5:00/23:00
No. 7	Wujianlou	Zoo Hub	18.6 km	20 min/11 min	5:00/23:00
No. 3	Dongzhimen	Jinjiacunqiaodong Station	19 km	13 min/11 min	5:30/22:00
No. 40	Muxiyuan Bridge North	Fifth Road Station	20.6 km	7 min/7 min	5:30/23:00
No. 46	Gaolou Village Station	Xidan Shopping Mall Station	9 km	10 min/10 min	5:30/22:00
No. 94	Beijing West Railway Station	Tayuannan	16 km	9 min/7 min	5:30/22:00
No. 141	Songjiazhuang Hub Station	Times Manor North Station	34 km	17 min/14 min	5:30/22:30
No. 200	Yongdingmen Bus Station	Yongdingmen Bus Station	38.3 km	15 min/10 min	5:30/22:30

5. Benefit analysis from PTV-UAV

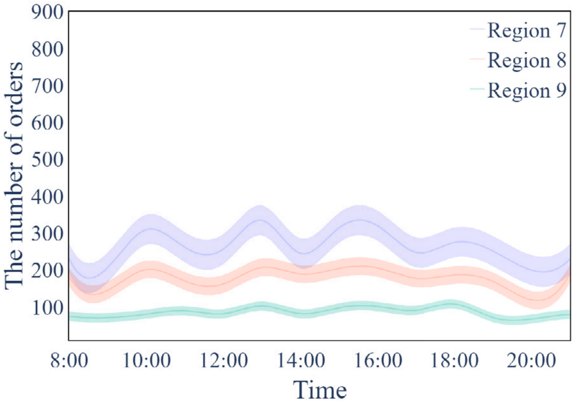
Following the analysis of spatiotemporal characteristics of prompt delivery orders and bus ridership, this section investigates the replacement of private vehicles with the PTV-UAV integration for prompt delivery and the benefits derived from this replacement. Section 5.1 quantifies the completion percentage of prompt deliveries through UAV-PTV integration across different recipient time tolerance levels. Section 5.2 forecasts future prompt delivery orders in Beijing and explores the potential operational revenue of PTV operators. Sections 5.3 and 5.4 evaluate the improvements in traffic efficiency and the reductions in exhaust emissions, respectively.

5.1. Time tolerance threshold

Timeliness is a primary challenge for UAV-PTV integration in prompt delivery. PTV stops are strategically located in high-traffic areas, such as residential areas, commercial areas, and educational institutions. However, PTV routes general aim to maximize area



(a) Regions 1 to 3 (b) Regions 4 to 6



(c) Regions 7 to 9

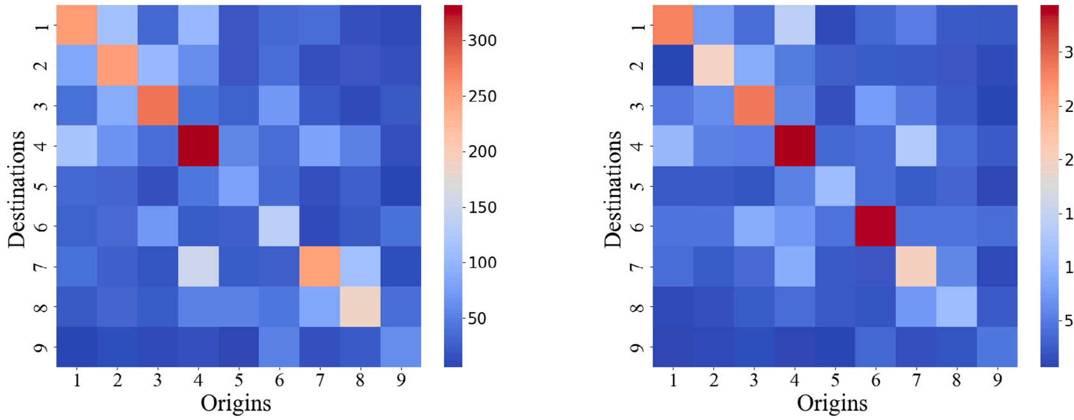
Fig. 6. Spatiotemporal characteristics of prompt delivery destinations.

coverage, often leading them on more circuitous paths during package deliveries. Consequently, for the same departure and arrival points, PTVs typically travel greater distances than private vehicles. However, UAVs can mitigate some of the inherent disadvantages of PTVs in prompt delivery. UAVs have the advantage of speed and direct deliveries between package points and PTV stops, outpacing walking couriers for first- and last-mile.

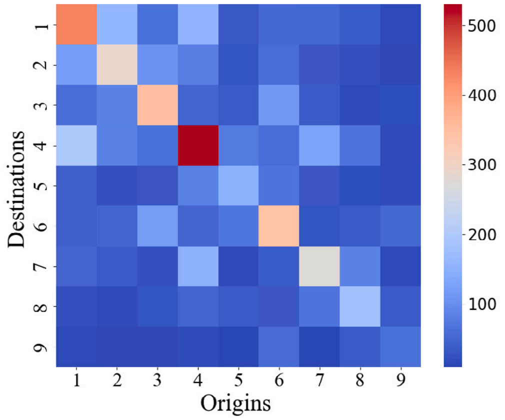
Table 2 shows the percentages of prompt deliveries completed within their original delivery time (i.e. in the time range of starting and ending of a prompt order in the data), achieved through PTV-UAV integration, for each origin–destination pair. For O-D pairs covering greater distances, UAV-PTV integration can fulfill higher percentages of on-time prompt deliveries. For instance, for the long-range O-D pairs 1-9, 2-8, and 9-1, the completion percentages are high, standing at 64.44%, 57.23%, and 70.00%, respectively. Conversely, for short-range O-D pairs like 5-2, 6-8, 9-8, and 1-2, the timely completion percentages by the UAV-PTV integration are relatively lower, standing at 7.62%, 9.31%, 10.70%, and 19.06%, respectively. When both origin and destination are within the same region, the integration typically registers lower completion percentages for prompt deliveries. This trend is observed in regions 1, 2, 4, 7, 8, and 9. This is primarily because, during short delivery spans, the fixed bus schedules significantly impact the delivery time compared private vehicles. Furthermore, detours made by UAVs from package collection points to bus stops considerably lengthen the overall delivery duration. Overall, the data suggests that UAV-PTV integration successfully completes an average of 30.16% of prompt deliveries within their original delivery time.

For short-distance delivery, the additional delay due to the PTV-UAV integration compared to private vehicle could surpass their original delivery time of using private vehicles, resulting in an unsatisfactory experience. This study uses a concept of ‘time tolerance’ to quantify the additional time recipients are willing to accept when opting for the PTV-UAV integration over private vehicles. Time tolerance is defined as the percentage increase in delivery time with PTV-UAV integration compared to private vehicles, expressed by

$$TT = \min\left\{\frac{|t_{PV} - t_{PU}|}{t_{PV}}, 1\right\} \times 100\% \tag{1}$$



(a) Morning Peak Period (b) Evening Peak Period



(c) Off-Peak Period

Fig. 7. Spatial characteristics of prompt delivery origin-destination.

Table 2
Proportion of delivery completed within the original delivery time for each O-D pair.

Destinations / Origins	1	2	3	4	5	6	7	8	9
1	15.31	19.06	18.41	20.69	39.35	59.87	27.72	44.07	64.44
2	24.64	16.94	17.76	12.65	11.67	18.12	45.93	57.23	36.67
3	15.45	19.71	13.56	48.72	37.24	26.23	41.93	54.62	1.82
4	23.89	13.96	50.42	21.47	22.07	51.82	25.59	10.31	56.21
5	33.16	7.62	41.01	20.37	16.39	19.48	11.77	28.37	50.00
6	51.52	20.66	25.46	55.09	26.24	17.66	49.01	9.31	14.65
7	37.24	54.72	40.15	25.89	14.59	56.76	16.92	18.91	12.11
8	62.68	62.31	56.54	22.85	24.07	14.68	15.22	15.74	11.29
9	70.00	56.67	22.31	65.45	37.74	13.84	11.18	10.70	9.45

where TT represents time tolerance, t_{PV} denotes the time taken by a private vehicle to complete prompt delivery, and t_{PU} represents the time required for the PTV-UAV integration to complete prompt delivery. The calculation, involving the minimum value between $\frac{|t_{PV}-t_{PU}|}{t_{PV}}$ and 1, aims to balance the impact of both large and small delays. Using time tolerance as an evaluative criterion, we aim to provide a more comprehensive and recipient-centric perspective on the feasibility of integrating PTVs and UAVs for prompt delivery, accounting for the diverse expectations of recipients. We examines the proportion of prompt deliveries completed via PTV-UAV integration for each O-D pair within the time tolerances of 10%, 20%, and 30%, as detailed in Tables 3, 4, and 5. Tables 3, 4, and 5 corroborate the trends identified in Table 2. For long-range O-D pairs, PTV-UAV integration demonstrates a high percentage of completion. However, for short-range O-D pairs, the completion percentage is relatively low. With time tolerances of 10%, 20%, and 30%, the average completion percentages of deliveries by PTV-UAV integration are 42.57%, 77.84%, and 87.42%, respectively.

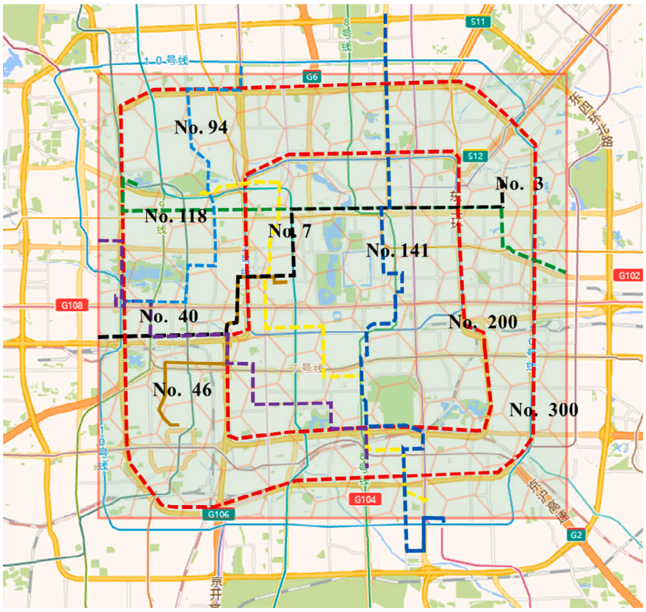
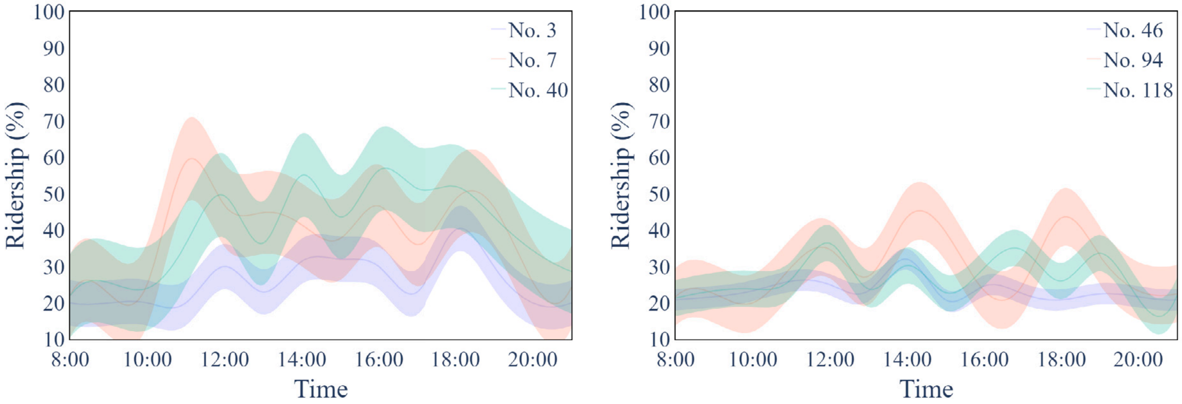
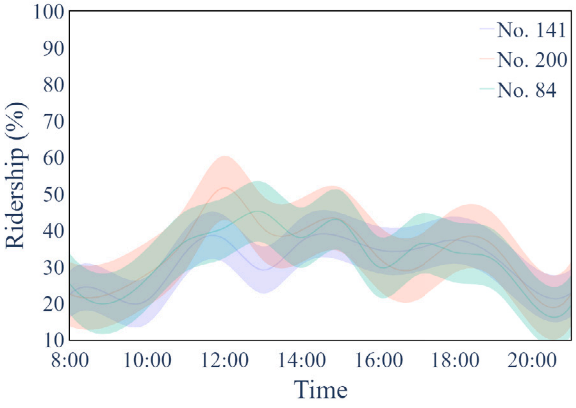


Fig. 8. Hexagon-based area division and bus lines.



(a) Bus Lines 3, 7, and 40

(b) Bus Lines 46, 94, and 118



(c) Bus Lines 141, 200, and 84

Fig. 9. Bus ridership.

Table 3
Proportion of delivery completed under 10% time tolerance for each O-D pair.

Destinations Origins	1	2	3	4	5	6	7	8	9
1	21.44	28.14	32.07	26.21	46.79	72.96	35.14	62.96	85.47
2	42.50	33.37	34.64	23.96	18.19	32.16	53.54	66.25	51.20
3	32.24	31.91	24.87	57.85	54.12	47.56	56.10	68.98	15.77
4	35.03	23.00	61.68	33.05	26.48	57.86	36.83	21.77	61.72
5	42.06	28.15	47.75	24.63	36.40	33.15	24.59	44.10	52.44
6	62.60	40.40	35.55	65.96	39.10	30.77	71.05	19.87	24.56
7	51.23	69.74	51.88	46.13	37.41	66.64	31.06	41.81	17.55
8	75.07	72.29	66.75	37.13	35.54	19.61	27.88	28.42	18.54
9	85.35	75.71	29.68	83.11	48.03	24.17	20.21	22.11	28.21

Table 4
Proportion of delivery completed under 20% time tolerance for each O-D pair.

Destinations Origins	1	2	3	4	5	6	7	8	9
1	52.94	65.88	80.74	79.41	88.02	100.00	67.85	97.46	100.00
2	70.91	60.34	79.23	57.74	51.85	85.71	75.31	87.52	97.50
3	77.02	60.87	49.03	98.24	82.75	71.01	96.44	100.00	48.28
4	67.34	65.09	100.00	63.38	74.59	100.00	65.23	57.76	86.20
5	91.85	85.40	88.34	51.51	61.11	60.24	61.23	83.78	99.40
6	100.00	70.23	83.99	89.31	93.65	73.45	90.00	69.08	55.29
7	92.56	100.00	70.18	90.70	84.14	100.00	66.76	78.41	51.87
8	100.00	100.00	95.12	80.50	68.99	65.15	60.22	70.34	68.98
9	100.00	100.00	72.09	100.00	89.41	36.52	51.26	71.13	70.41

Table 5
Proportion of delivery completed under 30% time tolerance for each O-D pair.

Destinations Origins	1	2	3	4	5	6	7	8	9
1	68.83	74.70	91.88	89.95	100.00	100.00	85.94	10.00	100.00
2	86.17	81.27	86.73	67.16	60.63	100.00	85.05	100.00	100.00
3	89.91	75.31	63.38	100.00	96.37	89.13	100.00	100.00	61.13
4	72.34	78.09	100.00	74.74	81.51	100.00	78.32	75.62	100.00
5	100.00	100.00	100.00	62.33	70.58	70.77	70.09	95.43	100.00
6	100.00	91.60	100.00	100.00	100.00	81.71	100.00	94.49	73.33
7	99.60	100.00	74.35	100.00	99.74	100.00	80.25	96.86	67.80
8	100.00	100.00	100.00	97.14	77.21	71.99	71.06	79.54	80.67
9	100.00	100.00	85.70	100.00	100.00	49.10	59.67	73.51	77.40

Notably, with a 30% time tolerance, the PTV-UAV integration nearly achieves timely completion for all deliveries, indicating that the integration of PTVs and UAVs presents a feasible solution for efficient prompt delivery.

Fig. 10 illustrates the average proportion of deliveries completed in different time tolerance with a 2.5% interval. Fig. 10 reveals that between a time tolerance of 0% to 2.5%, the delivery completion percentage experiences small increase with time tolerance. Within the 2.5% to 22.5% time tolerance range, there is a significant increase in the completion percentage as the time tolerance rises. Beyond a 30% time tolerance, the growth in the delivery completion percentage levels off and the complete percentage remains at 89.7%, irrespective of further increases in time tolerance. Thus, a 30% time tolerance is identified as the threshold at which PTV-UAV integration can effectively replace private vehicles in achieving prompt delivery. The increased delivery time of PTV-UAV integration could be compensated by some deduct in delivery cost for users, as the expenditure of PTV-UAV integration is cheaper than private vehicle delivery.

We explore further into the cost-effectiveness of PTV-UAV integration. This insight is pivotal in demonstrating that the 30% time tolerance can be effectively compensated through cost savings, thereby supporting the feasibility of UAV-PTV integration in prompt delivery. According to McKinsey Company (2024), the cost for short-range logistics delivery by UAVs ranges from $1.5 to $2. Given that UAV-PTV integration, UAVs perform short-range transport from the sender's address to the boarding bus stop and from the alighting bus stop to the recipient's address, so the cost of UAV should be counted twice. As reported by Beijing Municipal Commission of Transport (2024), the cost within 10 kilometers for using buses is $0.278, with an increase of $0.14 for every additional 5 kilometers. In Fengniao (2024), the prompt delivery includes both standard and dedicated services of using private vehicles, with charges comprising a base fee and additional costs related to delivery distance. For standard delivery, prompt delivery charges a base fee of $1.25, with distance-related costs of $0.14 per kilometer for 1–4 km, $0.21 per kilometer for 4–8 km, and $0.28 per kilometer for 8–100 km. For dedicated delivery, the base fee is $1.81, with distance-related costs of $0.14 per kilometer for 0–3 km, $0.21 per kilometer for 3–6 km, $0.28 per kilometer for 6–23 km, and $0.42 per kilometer beyond 23 km. Fig. 11 present the estimated delivery costs of PTV-UAV integration, dedicated delivery, and standard delivery for orders of different distances. 'PTV-UAV-1.5' and 'PTV-UAV-2' in the figure refer to the total delivery costs of PTV-UAV integration when the cost of short-range delivery conducted by UAVs is $1.5 and $2 per time, respectively. The result show that when the UAV delivery

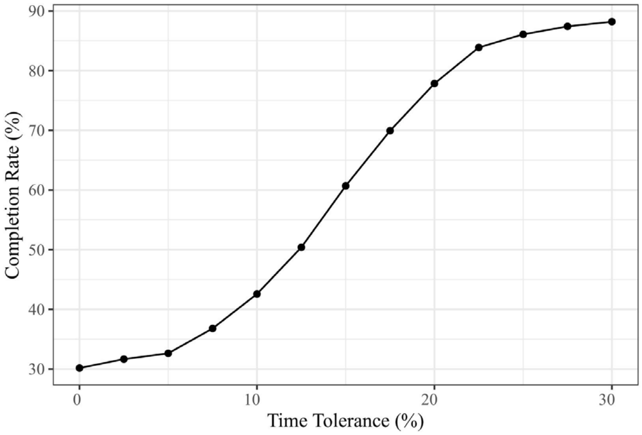


Fig. 10. Average proportion of prompt delivery completed by PTV-UAV integration with different tolerance time.

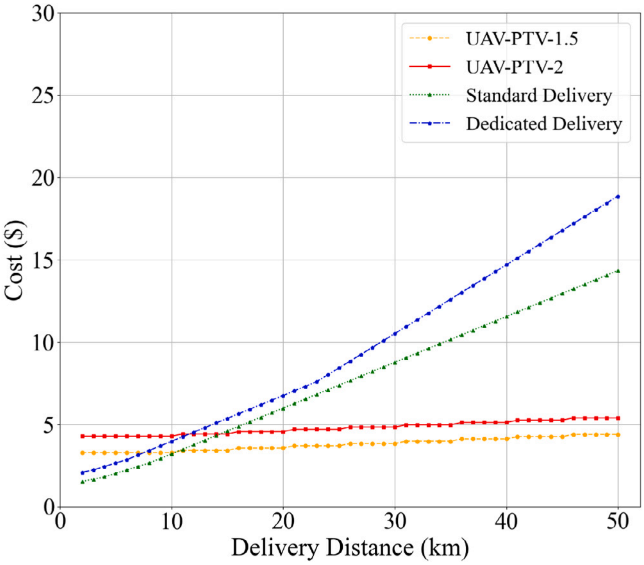


Fig. 11. Delivery cost under different delivery modes.

cost is $2 per time, both dedicated and standard delivery costs exceed 30% more than PTV-UAV integration at 19 km and 22 km. When the UAV delivery cost is $1.5 per time, dedicated and standard delivery costs exceed 30% more than PTV-UAV integration at 13 km and 17 km, respectively. Therefore, the 30% time tolerance threshold in the PTV-UAV integration mode can be effectively compensated by the reduction in 30% costs in these cases. The integration of UAVs and PTVs for prompt delivery could meet a significant completion portion of delivery with a 30% time tolerance threshold but also demonstrates considerable cost advantages.

5.2. Potential benefits of PTV-UAV integration on revenue

The integration of PTVs with UAVs, as an alternative to private vehicles for prompt deliveries, presents an opportunity to increase PTV operating revenues. We utilize intra-city express delivery data from Beijing Municipal Postal Administration (2023), detailed in Table 6, to forecast future prompt delivery demands, and estimate the potential for the operational revenue growth of PTVs resulting from their integration with UAVs. The analysis excludes intra-city express delivery data for the years 2020, 2021, and 2022, considering the remarkable influence of the coronavirus pandemic during these years. A linear regression model is calibrated to predict the prompt delivery demand in the future as shown:

$$y = 119.5 \times (x - 2013) + 346.6 \tag{2}$$

where y represents prompt delivery demand (units: millions) and x denotes the year. The R-squared value of the model is 0.493.

Table 6
Statistics on prompt delivery orders in Beijing (unit: thousands).

Month	2014	2015	2016	2017	2018	2019
January	24 040.8	35 529.4	62 673.0	63 785.0	97 884.4	66 162.5
February	18 833.1	21 900.8	42 406.7	53 570.2	74 168.3	39 347.0
March	24 204.0	35 011.6	67 348.6	63 012.7	91 852.4	61 054.6
April	25 314.2	34 652.8	66 449.1	54 960.7	85 428.8	59 105.6
May	27 126.7	37 852.0	69 039.4	78 441.4	91 205.9	56 851.4
June	27 795.9	41 191.3	84 504.3	96 416.7	106 199.2	65 329.1
July	28 037.5	38 529.5	71 716.1	77 287.6	92 636.5	59 787.0
August	27 598.6	35 637.8	76 432.8	107 813.0	95 998.8	59 339.6
September	30 486.7	38 878.6	77 590.5	98 030.5	99 142.6	60 426.9
October	30 531.5	38 316.7	78 394.9	100 741.2	92 584.6	58 428.3
November	36 904.3	56 198.5	84 671.7	126 224.7	121 229.4	75 083.6
December	39 075.6	53 893.3	77 766.4	117 860.7	107 283.8	66 554.2

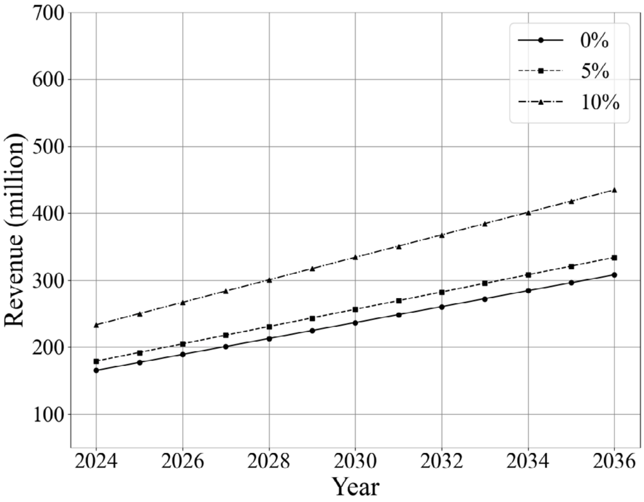


Fig. 12. PTV operating revenue under different time tolerances.

Fig. 12 shows the annual PTV operating revenue derived from PTV-UAV integration based on three distinct time tolerances: 0%, 5%, and 10%. With a time tolerance of 0%, PTV-UAV integration for prompt deliveries is estimated to generate operating revenue by $170 million in 2025. For time tolerances of 5% and 10%, the operating revenue increases by $341 million in the year 2035 and 2030, respectively. The results imply that the replacement of PTV-UAV integration with private vehicles for prompt delivery can significantly increase the operational revenue of PTVs, as an express delivery model.

5.3. *Traffic efficiency improvement*

Shifting prompt delivery from private vehicles to PTV-UAV integration could reduce road traffic as well by reducing logistic vehicles in the transport system. Our analysis data includes the trajectory (i.e. coordinates of vehicles in time series) of logistic vehicle for each prompt delivery order at a time resolution of 15 s. Meanwhile, the data enables the estimation of average vehicle speeds on each road segment. To understand the potential improvement in traffic efficiency thanks to the replacement of PTV-UAV integration to private vehicles for prompt deliveries, we estimate the increase in traffic flow volume in road segments due to less private logistic vehicles substituted by PTV-UAV integration. Specifically, the fundamental diagram theory posits that for any road link a, flow Q_a is the product of density k_a and speed v_a, i.e., $Q_a = k_a v_a$. We utilize the classic Newell nonlinear model to depict the complex relationship between traffic density (k_a) and speed (v_a).

$$v_a = v_f \left\{ 1 - \exp\left\{ -\frac{\lambda}{v_f} \left\{ \frac{1}{k_a} - \frac{1}{k_j} \right\} \right\} \right\} \tag{3}$$

where v_f represents the free-flow speed, k_j is the jam density, and λ is the slope of the tangent at the initial point, capturing the relationship between vehicle speed and headway. In practice, λ takes the value as the reciprocal of the driver's reaction time. Following Zhang et al. (2018), the parameters v_f, k_f, and λ are set to be 106 km/h, 167 veh/km, and 1.25 s^{-1}, respectively. Eq. (3) allows inference of the traffic density from the speed of a road link calculated from vehicle trajectory data of logistic vehicles for prompt delivery. Based on fundamental diagram, the traffic flow volume of a road link can be calculated based on density and corresponding speed. The mean road density of the studied region is 11.65 $\mathrm{km/km^2}$. The reduced traffic density is calculated based

Table 7
The flow increase ratios under different time tolerances.

Time tolerance	1%	5%	10%	15%	20%	25%	30%
Flow increase ratio	0.27%	0.75%	1.35%	1.94%	2.53%	3.11%	3.7%

on the reduced number of private vehicles in the area due to PTV-UAV integration for prompt delivery. Afterwards, Eq. (3) is used to calculate the average speed after traffic reduced, which can further calculate the traffic flow volume after the reduction in the number of vehicles.

Table 7 presents the improvement in traffic flow volume across different time tolerance levels for PTV-UAV integration. With time tolerances of 1%, 10%, and 15%, the traffic flow volume increases 0.27%, 1.35%, and 1.94%, respectively. Under the time tolerance threshold of 30%, the traffic flow volume increases by 3.7%. The practical implication is that PTV-UAV integration for prompt delivery has the potential to improve traffic situations and alleviate traffic congestion issues in the central city areas. The annual congestion-associated costs per vehicle in Beijing – including both time-related and fuel consumption expenditures – are estimated at $1899 million. Hence, 3.7% in traffic flow volume could yield substantial benefits by reducing societal cost due to traffic congestion.

5.4. Emission reduction

The potential for emission reduction through the integration of PTVs and UAVs replacing private vehicles for prompt delivery, includes two different aspects. Firstly, a direct reduction in emissions results from the decreased use of private vehicles. It is assumed that a single vehicle emits approximately 152 grams of emission per 100 kilometers traveled (Dazhong, 2011). The second aspect involves reduced emissions resulting from increased average speed. This study employs the average speed model from Ryu et al. (2015), adept at calculating link-specific carbon dioxide emissions. The carbon emissions g_a (unit: $\mathrm{g/min}$) for vehicles on link a are calculated as follows:

$$g_a = Q_a \times l_a \times EF_a \tag{4}$$

where Q_a is the traffic flow on link a (unit: $\mathrm{veh/min}$), l_a is the length of link a (unit: km), and EF_a is the emission factor (unit: $\mathrm{g/km^{-1}}$). It is assumed that all vehicles are light-duty gasoline vehicles. Utilizing the work of Ryu et al. (2015), the emission factor is calculated by

$$EF_a = \begin{cases} 87.58 \times (v_a)^{-0.6}, & 0 < v_a < 65 \text{ km/h} \\ 0.0363 \times v_a + 5.25, & v_a \geq 65 \text{ km/h} \end{cases} \tag{5}$$

where v_a represents the average speed of vehicles on link a.

Fig. 13 illustrate how emission reductions correlate with decreased inter-regional demand. It reveals a pattern that reductions in emissions along the diagonal consistently appear as the most substantial, indicating that the carbon emissions from prompt delivery orders with both origin and destination in the same region are reduced the most. The decrease in exhaust emissions for prompt delivery orders with original and destinations in adjacent regions is secondary. For instance, emissions significantly decrease for deliveries from region 1 to regions 2 and 4, as well as from region 3 to regions 2 and 6. This pattern suggests that prompt delivery orders are still mainly concentrated over short distances.

Replacing private vehicles with PTV-UAV integration for prompt delivery is estimated to reduce emissions by 0.171 tons per hour. This is equivalent to an annual reduction of 811.40 tons of carbon emissions through this integration (only the thirteen hours from 8 a.m. to 9 p.m. in Fig. 9 are considered). Since the area in Fig. 3 accounts for 1.18% of the total area of Beijing, it is estimated that this integration can reduce carbon emissions by 68,762 tons per year. It is reported that the annual carbon footprint in Beijing is about 150 million tons (Qianlong, 2023). Emissions from road transportation (including private vehicles, freight trucks, and buses) account for 17% (Qianlong, 2023). Therefore, replacing private vehicles with PTV-UAV integration for prompt delivery equates to a 0.27% reduction in exhaust emissions. Taking the cost of addressing one ton of carbon dioxide ranges between $50 and $60, PTV-UAV could potentially lead to savings of approximately $3.43 million in carbon dioxide mitigation expenses, which is pretty substantial.

6. Conclusion and discussion

This study explores the potential effects of integrating PTVs and UAVs as a potential replacement for traditional logistic vehicles for prompt delivery. Even without accommodating any time tolerance, the integration of PTVs and UAVs for prompt delivery is estimated to potentially increase PTV operating revenue by $17 billion in 2025. The integration could also lead to benefits on traffic flow volume in the road network with an increase of up to 3.7%. Additionally, the integration of PTV and UAV could contribute to much reduction in emissions thanks to replacing private vehicles for prompt delivery, which is up to 68,762 tons per year. The quantitative results not only demonstrate the substantial advantages of the PTV-UAV integration but also encourage urban planners and policymakers to reconsider modern city logistics.

In light of the findings and insights derived from this study, there are several practical policy implication to effectively encourage the integration of UAVs and PTVs for prompt delivery. The integration of UAVs and PTVs significantly benefits from a robust

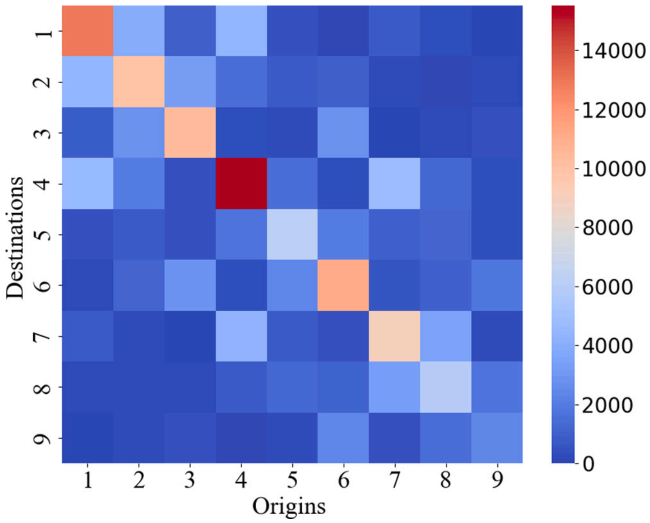


Fig. 13. Emission reduction heat map (unit: g/h).

infrastructure of public transit. Cities with advanced and well-developed public transport networks are easier to pioneer the implementation of the technology. Not only will PTV-UAV integration assist in optimizing the existing logistic infrastructure, but it will also supplement the revenue streams for public transport operators. Efficiently utilizing airspace and roadways with UAVs and PTVs could offset the environmental and congestion of traditional road transport as well. Densely populated urban areas such as New York, London, and Tokyo, stand to gain greatly from these prompt delivery services. The adoption and utilization of UAVs and PTVs are likely to vary depending on different urban contexts. Metropolises and major urban centers are expected to exhibit higher demand, driven by their intense demand. However, these areas may also pose logistical challenges such as constrained airspace and limited UAV landing spots. Infrastructure upgrades, including designated UAV corridors and dedicated PTV lanes, may be helpful. Conversely, less developed areas such as rural regions or smaller towns, with lower demand yet greater adaptability, could greatly benefit from partnerships with major delivery companies. Through the integration of UAVs and PTVs, these regions have the potential to achieve quicker delivery times and improved connectivity, thereby avoiding the need for extensive private vehicle delivery. There are some potential safety issues with UAV in the current urban environment. In particular, many countries, such as Australia, have adopted strict regulations and restrictions to regulate UAV in urban areas. These regulations are established to ensure public safety and the protection of the urban environment. Therefore, coordination with these regulations can ensure the feasibility and safety of UAV-PTV integration. In future studies, working closely with government and regulatory agencies and considering city-specific regulatory requirements will be critical steps to ensure successful implementation of UAV-PTV integration for logistic delivery. Despite the challenges, UAV-PTV integration may provide more efficient and sustainable solutions for future urban logistics after in-depth research and collaboration on security with public authorities.

CRediT authorship contribution statement

Shaohua Cui: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Ying Yang:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Kun Gao:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Heqi Cui:** Data curation, Formal analysis, Methodology, Software, Visualization. **Arsalan Najafi:** Data curation, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This research is supported by Energimyndigheten, Sweden through e-FAST project (project number: P2022-00414), JPI Urban Europe through e-MATS project (project number: P2023-00029), and Area of Advance Transport at Chalmers University of Technology.

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