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Assessing the Future Role of Unmanned Aircraft Systems in Urban Logistics: Opportunities, Risks and Systemic Impacts

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Abstract

Rising freight volumes driven by e-commerce growth and innovation in delivery concepts are transforming last-mile logistics. Unmanned aircraft systems (UAS) are discussed as a potential solution, provided their deployment aligns with political, societal and environmental objectives. This study evaluates the opportunities and risks of UAS in last-mile parcel delivery, focusing on whether efficiency gains can be achieved without increasing environmental impacts or compromising public safety. A case study of the Aachen city region analyses courier, express and parcel logistics under three scenarios: a status quo relying exclusively on electric light commercial vehicles (Scenario A), a multimodal system in which heavy-lift drones supply decentralised parcel stations (Scenario B), and a direct-to-customer concept using lightweight parcel drones (Scenario C). An integrated modelling framework combines unmanned aviation modelling, multi-agent transport simulation, route optimisation and microscopic traffic flow analysis based on a synthetic population reflecting regional mobility patterns. The assessment addresses traffic effects and road safety, economic performance, social acceptance and noise exposure, legal operationalisation, and stakeholder involvement. Results indicate that UAS can significantly reduce road mileage, vehicle stops and fleet size, particularly in Scenario B, which shows the most favourable ecological and economic performance due to flow consolidation at parcel stations. In contrast, Scenario C leads to fleet expansion, operational constraints and concentrated noise impacts at take-off and landing sites for UAS. While potential safety benefits arise from reduced road traffic, empirical evidence on UAS–ground transport interactions remain limited. Although both UAS scenarios reduce transport costs, social acceptance is low and legal implementation remains complex. Overall, UAS offer efficiency and cost-saving potential, but regulatory, societal and environmental constraints are likely to restrict near-term applications to niche use cases.

Keywords: unmanned aircraft systems; last-mile logistics; scenario modelling; drone integration; environmental impacts; public acceptance; regulatory frameworks

1 Introduction

The rapid growth of e-commerce has substantially increased urban freight transport, intensifying congestion, air pollution, and noise, and affecting quality of life. Municipalities and logistics providers face pressure to develop more efficient, climate-friendly, and space-efficient transport systems, as conventional ground-based solutions increasingly reach their limits. Unmanned aircraft systems (UAS), or drones, offer a potential solution by shifting selected freight movements from the ground to the air, reducing congestion, emissions, and delivery times, especially for time-critical and small-scale deliveries such as medical supplies (Association for Unmanned Aviation, 2021). However, large-scale urban drone deployment raises uncertainties regarding environmental, energy, and societal impacts. In addition, comparisons with ground-based transport suggest potential environmental benefits in specific applications, though operational-scale validation remains limited. (Stolaroff et al., 2018) Challenges include noise, airspace complexity, privacy and safety concerns, and effects on urban landscapes and wildlife. Legal and planning issues, such as flight corridor regulation, take-off and landing infrastructure, and safety compliance, are still evolving (EASA, 2021).

This study systematically assesses the impacts of partially shifting urban freight to drones, focusing on conditions for sustainable, energy-efficient, and socially acceptable operation. Key research questions address the traffic, economic, environmental, and societal effects of drone integration, their potential to reduce emissions and congestion, and the legal, infrastructural, and societal requirements for safe deployment. A multi-stage, model-based framework combines literature review, policy analysis, and simulation of drone and ground-based transport, applied to the urban region of Aachen, Germany. The study evaluates modal shifts, emission impacts, and societal aspects including public acceptance, noise, and infrastructure integration. Results inform initial policy and planning recommendations for environmentally and socially

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responsible drone-based delivery. By linking simulation with multidisciplinary assessment, the study provides evidence-based insights for integrating UAS into sustainable urban freight transport. The presented paper is structured as follows: In chapter 2, the State of the Art in health and environmental impacts of drones as well as in transport modelling of ground-based and air traffic is presented. In chapter 3, the modelling procedure and the scenario development is described. Afterwards, the simulation results are shown. Based on this, the results are critically discussed and recommendations for action are derived. Finally, this study concludes with a brief summary and an outlook.

2 State of the Art

2.1 Health and Environmental Impacts

Drone-based logistics may reduce energy consumption and CO_2 emissions depending on system design (Linchant et al., 2015), but they also raise environmental, health and social concerns. Noise represents the main health-related impact, while visual disturbance, light emissions and distraction may additionally affect humans (ITF, 2018). Further concerns include impacts on wildlife as well as land take and soil sealing associated with logistics hubs (ITF, 2021). Prolonged noise exposure can cause stress, sleep disturbance and cardiovascular effects, particularly in urban areas (Fons-Esteve, 2018). Drone noise differs from road traffic noise in its higher frequency content and dependence on vehicle characteristics, while vibrations from small drones are negligible. Noise perception is strongly context- and individual-dependent (Christian & Cabell, 2017). Mitigation measures such as route optimisation (e.g., through no-fly zones, higher flight altitudes) and low-noise operations are relevant for planning approval under German building, land-use and noise protection legislation (German Building Code §§ 1, 8, 30–35; German Land Use Ordinance §§ 2–11; Federal Immission Control Act; DIN 18005). Visual disturbance is more pronounced where operations lack transparency, whereas authorised flights are better accepted (Bakx & Nyce, 2017). Soil sealing can be reduced through integration into existing facilities and proactive planning, supported by research from RWTH Aachen and DLR. Despite predominantly electric propulsion, comprehensive life cycle assessments remain necessary, and advanced air traffic models increasingly integrate noise and acceptance criteria to enable environmentally sensitive routing.

2.2 Transport Modelling (Ground-Based and Air Traffic)

Assessing the effects of shifting freight transport from road to air requires an integrated modelling framework combining MATSim with the vehicle routing solver Jsprit, whilst local disturbances caused by delivery vehicles are analysed using microscopic traffic flow simulations with Vissim.

2.2.1 Modelling of Ground-Based Transport

Urban freight transport modelling focuses on trip-, tour- and agent-based approaches. Disaggregated tour-based models capture spatio-temporal vehicle movements (Machledt-Michael, 1999; Hunt & Stefan, 2007), while hybrid and agent-based models represent heterogeneous actors and decision-making along supply chains (Routhier & Toulier, 2007; Wisetjindawat et al., 2007; Roorda et al., 2010). Recent advances include empirically calibrated agent-based models for Singapore and the Netherlands (Sakai et al., 2020; de Bok et al., 2019). In the present study, freight transport is modelled using Jsprit linked with MATSim, building on established applications in urban logistics and courier, express and parcel transport (Schröder et al., 2012; Thaller 2018).

Integrated urban passenger and freight models remain rare, particularly at the urban scale. Existing applications, such as SMART-FM in Singapore, analyse interactions between passenger and freight transport but treat freight demand independently from passenger behaviour (Alho et al., 2018; Sakai et al., 2020). An integrated agent-based approach combining MATSim and Jsprit was proposed by Schröder and Liedtke (2017) and is adopted in this research.

Traffic flow modelling in congested urban networks allows the simulation of local congestion effects caused by delivery vehicles stopping in traffic lanes, which cannot be adequately represented by conventional assignment methods. Microscopic simulation tools such as Vissim therefore complement network-wide models. Vissim is based on the Wiedemann car-following model and includes detailed lane-changing behaviour, providing state-of-the-art accuracy for local traffic flow analysis despite high computational requirements (Fellendorf & Vortisch, 2010; PTV AG, 2019).

2.2.2 Modelling of Air Traffic

At the air traffic level, the European regulatory framework for UAS has been in force since December 2020, defining the OPEN, SPECIFIC and CERTIFIED categories according to operational risk (European Commission, 2019). A range of performance models for UAS is available, extending from simplified point-mass approaches to highly specific and validated models tailored to individual UAS types. A key differentiation is made between fixed-wing UAS and vertical take-off and landing capable aircraft (VCA). For instance, provides the Base of Aircraft Data (BADA), which includes performance models for almost all fixed-wing aircraft operated in Europe and has been expanded to cover remotely piloted aircraft systems (RPAS), representing a subset of fixed-wing UAS. BADA delivers standardised mathematical descriptions of aircraft performance parameters, thereby supporting the modelling and simulation of flight paths and trajectories. At present, however, BADA does not include performance models for VCA of the type considered in this study. Such UAS may instead be represented through software-in-the-loop simulations, where either a physical UAS or solely its controller operating on dedicated hardware generates realistic output data without conducting an actual flight. One example is the flight controller. This approach is, however, constrained to a limited number of simulated UAS, as the available controller hardware constitutes the primary limitation. For larger-scale simulation environments, (2021) proposes a copter flight management system (CFMS). Kuenz & Peinecke (2012) implements risk-based flight path consolidation using dedicated air traffic simulation tools that enable precise four-dimensional trajectory planning and optimisation with respect to efficiency, noise and environmental impacts.

2.2.3 Optimisation Approaches for Drone-Based Logistics Operations

Drone logistics concepts can be distinguished between independent Drone Operations (DO) and combined Drone-Truck Operations (DTCO) (Chung et al., 2020). As this study focuses on DO scenarios, modelling approaches are largely derived from Travelling Salesman and Vehicle Routing Problems, reflecting limited range and payload similar to electric vehicles (Otto et al., 2018). Additional challenges arise from three-dimensional movement (Kuenz et al., 2015; Furini et al., 2016), mandatory depot returns and high operational speeds, which require dynamic and stochastic optimisation approaches (Kuenz, 2015; Coelho et al., 2017).

3 Methodological Procedure

In this chapter, the modelling approach used in this study will be presented. This approach enables to analyse the modal shift from ground-based freight transport to drones and its impacts on environment and society. In addition, the scenarios developed will be described, which are subsequently simulated within the models.

3.1 Modelling procedure

Various simulation models were employed to represent ground-based passenger and freight transport and unmanned air traffic, examining effects of deploying unmanned aviation compared with ground-based freight transport handling. These models were linked with one another. For modelling air traffic, Gridcity (Peinecke & Kuenz, 2017) and the copter flight management system CFMS (Naser et al., 2021) were used. MATSim is a widely applied open-source framework that simulates individual activity plans and route choice using evolutionary algorithms and queue-based network loading (Horni et al., 2016). In this project, an existing MATSim model of the city region of Aachen is used and jointly assigned with freight demand (Burla & Tauer, 2019). MATSim is linked to the Vehicle Routing Problem (VRP) solver jsprit which optimises the ground-based freight transport and generates the tours conducted (Schröder et al., 2012). The traffic flow analysis was conducted using Vissim (2023). All simulation tools were adapted as necessary to the local conditions of the Aachen urban region in order to achieve a realistic simulation.

Using jsprit, the routes of the electrically powered light goods vehicles (e-LGVs) were generated and transferred to MATSim, Vissim and Gridcity. The data input from jsprit was relevant for MATSim in order to simulate freight transport together with overall passenger transport in the Aachen urban region and, on this basis, to represent resistance within the infrastructure network for freight transport in a realistic manner. By jointly simulating passenger and freight transport in MATSim, heavily loaded road sections were identified. The affected road sections were modelled exemplarily in Vissim, simulated, and the results were subsequently extrapolated to the entire region. The routes intended for air traffic were transferred to Gridcity, with particular emphasis on take-off and landing points. In this context, take-off points were the distribution centres of the CEP service providers, while the parcel stations to be served (Scenario B) and private households (Scenario C) constituted the landing points. In Gridcity, these requirements were translated into trajectories through planning with the CFMS software, which were subsequently analysed statistically. Detailed information on the modelling procedure is described in Lieb et al. (2026a).

3.2 Scenario definition and development

This study examined impacts of shifting traffic from ground to air, focusing on drone/UAS applications in leisure, goods transport, parcel delivery, inspection, monitoring, and authorities and security organisations. Manned aviation was excluded. Transport demand and impacts were quantified using interlinked simulation models. Future developments were explored using a "what if" approach and the Cross-Impact Balance (CIB) method to ensure internally consistent scenarios (Weimer-Jehle, 2018). The study area was the Aachen urban region, comprising approximately 563,000 inhabitants and 700 km², with diverse urban, suburban and rural structures (Städteregion Aachen, 2024). Pandemic-related effects were excluded. Three scenarios were analysed: Scenario A – Status Quo, Scenario B – Parcel Stations, and Scenario C – Direct Delivery. ***Scenario A – Status Quo*** represents the current situation with no significant drone operations. Urban mobility is entirely ground-based transport, including walking, cycling, private motorised transport and public transport. Parcel delivery by CEP service providers uses e-LGVs with a permissible gross vehicle weight of 3.5 tonnes, operating from eight distribution centres delivering combined business-to-consumer (B2C) and business-to-business (B2B) consignments. ***Scenario B – Parcel Stations*** shifts part of CEP freight transport to air. Two centrally located vertihubs (take-off and landing sites for drones) supplement the eight distribution centres. Heavy-lift drones deliver parcels to 317 parcel stations, with locations optimised for uniform population coverage. Recipients collect consignments from parcel stations. Consignments exceeding 10 kg and all B2B consignments are delivered conventionally by e-LGVs. The electrically powered drones achieve speeds of 5–10 m/s with flight endurance of approximately 45–60 minutes, resulting in an operational radius of 9–18 km from the vertihub. ***Scenario C – Direct Delivery*** involves direct drone delivery using light UAS with maximum payload of 5 kg. These drones reach flight speeds of 10–18 m/s with approximately 30 minutes flight time, corresponding to an operational radius of 9–16 km. Six distributed vertihubs serve as base stations. Due to lower payload capacity, a larger share of parcels is delivered conventionally by e-LGVs, and all B2B consignments are excluded from drone delivery. Further information on the scenario development process and the parametrisation of each scenario can be found in Lieb et al. (2026a) and Ghazal et al. (2025).

4 Simulation results

In the following, the simulation results for the three modelled scenarios will be presented. Detailed descriptions of the simulation results can be found in Lieb et al. (2026a).

4.1 Land use for the take-off and landing infrastructure

The use of drones for parcel deliveries requires space for take-off and landing infrastructure. Land use should be minimised, especially in urban areas with competing demands. Different requirements must therefore be weighed in the planning process. Potential vertihub locations were identified for two scenarios in the Aachen metropolitan area. Exclusion zones where drone operations are prohibited – residential areas, sensitive facilities, and security-relevant sites – were defined based on the current land use plan. Other areas, such as commercial or public-use land, were also considered for future use. For Scenario B, “parcel stations,” take-off and landing points were defined. Parcel stations, placed according to demand, are suitable at bus stops, parking facilities, petrol stations, taxi ranks, and aviation areas, offering sufficient space and high pedestrian traffic with minimal additional land use. Using Location-Allocation, 317 potential parcel stations were selected. Two vertihub sites were identified: Aachen-Merzbrück airfield and a helicopter landing site at the Disaster Control Centre in Simmerath. For Scenario C, “direct delivery,” multiple vertihubs serve as take-off points, while landing is assumed near households. Potential vertihub locations are similar to Scenario B, but only larger bus stations were considered. Six vertihub sites were selected using Location-Allocation. In summary, the chosen traffic areas enable a dense drone logistics network with minimal new land use, primarily requiring land conversion. However, prioritisation of land use and site-specific assessments remain necessary.

4.2 Traffic Impacts

By shifting a portion of parcel demand to the air, only a minor change in ground-based transport patterns is expected. The simulation results provide general indicators for the logistics concept regarding the number of vehicles and drones required, the number of tours and flights, and the total mileage performed. Furthermore, the detailed modelling allows the effects of this modal shift to be represented, enabling the assessment of impacts on traffic safety and flow. The analysis first considers the size of the vehicle fleet in comparison across the scenarios. Figure 1 shows the number of vehicles required, including drones, for each delivery scenario. It can be seen that Scenario “Parcel Stations” requires the fewest vehicles, with just under 600. In contrast, Scenario “Direct Delivery” requires the highest number, at 785 vehicles. Compared to the “Status Quo,” which requires 726 vehicles, the vehicle count is reduced by 18 % in Scenario “Parcel Stations” and increased by 8 % in Scenario “Direct Delivery.” The lower number of vehicles in Scenario “Parcel Stations” is primarily due to deliveries being made to the 317 parcel stations across the study area rather than directly to end customers. The larger fleet for “Direct Delivery” results from the limited transport capacity of the small parcel drones, which is only 5 kg. In both scenarios, a similar number of e-LGVs – around 270 vehicles – is required, for example, to transport heavier parcels or to fulfil business-to-business (B2B) deliveries.

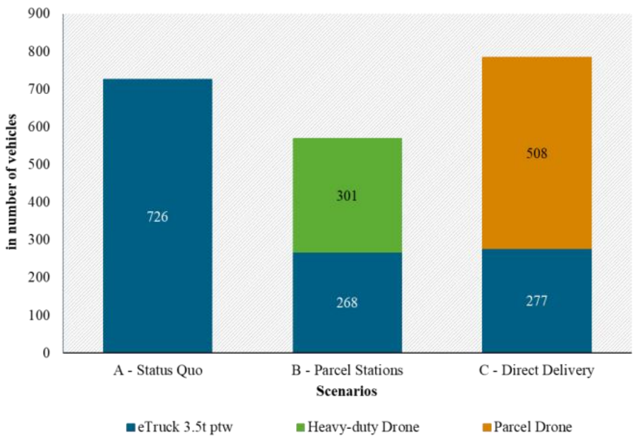

Fig. 1. Comparison of scenarios regarding the number of vehicles used

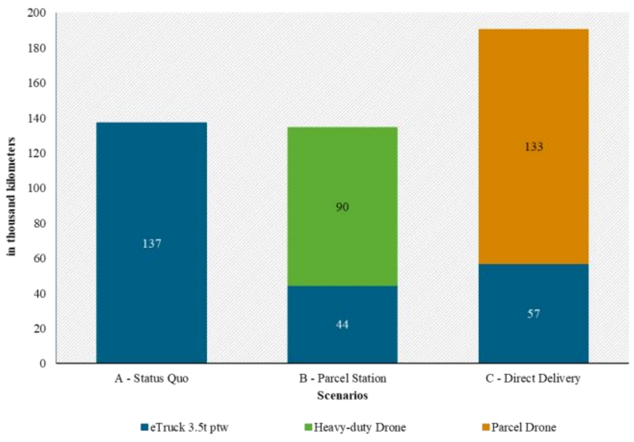

Fig. 2. Comparison of scenarios regarding mileage performed (without restricted airspace)

Figure 2 shows the simulation results for total mileage (i.e., vehicle kilometres) without flight restriction zones, broken down by vehicle type for the three scenarios. In Scenario B – “Parcel Stations” (approx. 134,400 km), total mileage is 2 % lower compared to Scenario A – “Status Quo” (approx. 137,300 km). Thus, although fewer kilometres are travelled in this scenario than in the other two, the difference from the Status Quo is only marginal. In Scenario C – “Direct Delivery,” a total of approximately 190,400 km is covered, corresponding to around 40 % more mileage compared to the Status Quo. In the scenarios involving drones, roughly two-thirds of the total mileage is attributed to drones, with the remainder covered by e-

LGVs. Overall, Scenario B – “Parcel Stations” has the lowest vehicle mileage. However, when flight restriction zones are taken into account, the required drone mileage would be higher in both scenarios. The high mileage of drones is primarily due to the fact that e- LGVs, thanks to their large load capacity, can consolidate many deliveries into a single tour. Drones, on the other hand, must return empty to the vertihub of the distribution centre after each delivery before they can pick up additional cargo. Other factors influencing the mileage of the deployed vehicles include: (i) Decentralised location of distribution centres compared to centrally located vertihubs, (ii) detour factors in ground traffic compared to direct flights along the straight line, and (iii) ground delivery route planning, for example due to fixed delivery time windows. In both scenarios involving drone traffic (B – “Parcel Stations”, C – “Direct Delivery”), the reduction in ground vehicle mileage is of a similar magnitude, amounting to 68 % and 59 % across the entire modelling region, depending on the scenario. The two scenarios differ in that parcel deliveries by drone are either made directly to recipients or to a parcel station. Conventional road-based parcel delivery cannot be completely eliminated, as some shipments exceed the maximum payload of the drones (5 kg or 10 kg, depending on the scenario). Although the reduction in CEP traffic is significant, delivery vehicles represent only a small share of total ground traffic. Considering all traffic, the reduction in mileage is only around 1 % in both drone delivery scenarios. The extent to which this slight decrease in total mileage affects traffic safety can only be estimated. While fewer vehicle kilometres generally reduce the number of accidents, lower traffic volumes may lead to higher speeds, which in turn slightly increases accident risk. Overall, the reduction in total mileage is expected to have a neutral to positive effect on traffic safety. Regarding traffic flow, an improvement is expected in both drone traffic scenarios. The number of stops made by CEP vehicles is reduced by approximately 85 % when using “Parcel Stations” and by around 80 % for “Direct Delivery.” This significantly reduces the disruption to moving traffic caused by stationary vehicles. The high number of eliminated stops results in a noticeable reduction in lost time for all moving traffic, even though the improvement for any individual vehicle may be small. In summary, Scenario “Parcel Stations” would provide a benefit from drone use, reflected in a lower number of vehicles and total mileage. In contrast, Scenario “Direct Delivery” would lead to an increase in both indicators. The shift from ground to air transport, in the context of the current overall volume of road traffic, would have only minor effects on traffic safety and flow.

4.3 Economic Impacts

The following section analyses the economic effects on ground transport and on drone traffic for the three scenarios defined. Figure 3 shows the daily total transport costs for both ground-based freight transport and drone traffic. In both modelled scenarios involving drone operations, a significant reduction in transport costs can be observed compared to the Status Quo. This applies to both scenarios under both optimistic and pessimistic assumptions (see Lieb et al. 2026). From an economic perspective, the comparison of the simulation results across scenarios highlights that direct delivery to customers by drones in urban areas represents a considerable challenge, as a (very) large number of drones would be required. This would necessitate substantial investment by drone operators or logistics service providers to maintain the necessary infrastructure (e.g., take-off and landing sites), the high number of drones, and the required personnel. A limitation of the results regarding the transport costs of the drones is that these are, so far, preliminary and highly theoretical cost estimates with considerable uncertainties, which need to be refined in further research activities.

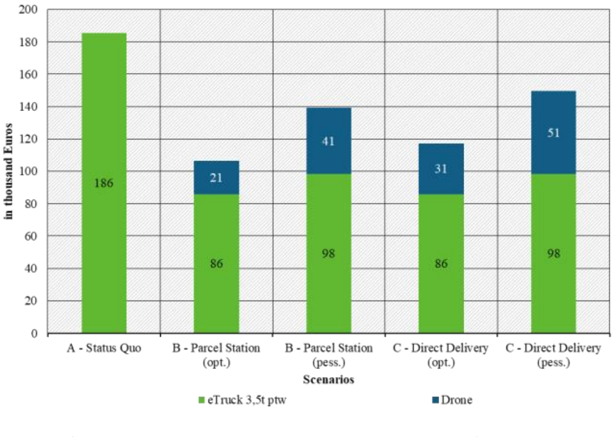

Fig. 3. Comparison of scenarios regarding daily total transport costs for ground-based and air traffic

4.4 Social Acceptance and Health Impacts

Regarding the social acceptance of drone operations, the literature review (see Chapter 2.2) indicates that public opinion on future drone use is divided. Attitudes towards drones are influenced by various factors. On the one hand, demographic factors such as gender, age, education, income, and place of residence play a role. On the other hand, experience, information about benefits and risks, and transparency regarding the reasons for drone deployment also shape public perception. Environmental noise in general represents one of the largest environmental health risks, according to the World Health Organization (WHO, 2018). Similarly, the literature review identified negative effects and concerns associated with drone noise. The extent to which drone noise is perceived as disturbing is influenced by various flight parameters (e.g., flight altitude, flight distance, flight mode) and drone characteristics (e.g., size, model), as well as by contextual factors (location, time of day, visibility of drones) and personal attitudes. Overall, the relationship between these influencing factors appears to be complex and requires further research. Based on the modelling, the expected noise exposure for scenarios involving drone operations is summarized below. More details, especially regarding the scenario “Parcel Stations”, can be found in Lieb et. al. (2026a,b). The simulation results indicate that higher noise exposure is primarily expected at the take-off and landing points (i.e., vertihub) of the drones. For the “Parcel Stations” scenario a maximum noise exposure of 66.0 dB(A) at the site of the most frequently used vertihub was simulated. For the “Direct Delivery” a maximum noise exposure up to 67,0 dB(A) was obtained. Hence, the vertihub locations should be selected carefully. During en-route flight a minimal noise impact between 28 and 56 dB(A) at ground level is expected. With respect to visual pollution, no recognised metrics currently exist to quantify the visual impact on the public from potentially high future drone traffic. However, it seems reasonable to assume that visual impact from drones is likely influenced by two factors: (1) **Presence probability:** The likelihood of observing a drone at any given time in the sky. (2) **Concurrency:** The number of drones observed simultaneously in the sky. Both metrics were determined for the modelled scenarios. Based on the applied modelling, visual pollution is summarized below. A more detailed analysis can be found in Lieb et. al. (2026a,b). The average presence probability (%) and the maximum concurrency are higher in the “Direct Delivery” scenario than in the “Parcel Stations” scenario. Consequently, the likelihood of observing a drone at any given time in the sky, as well as the number of drones seen simultaneously, is increased. For the “Parcel Station” scenario the average presence probability is 5% and the maximum concurrency of drones is above 8 drones. For the “Direct Delivery” scenario the average presence probability is 14% and the maximum concurrency of drones is above 10 drones. In both scenarios, the maximum presence probability, determined at the vertihubs, is considerably higher than the average with 43% for the “Parcel Station” scenario and 42% for the “Direct Delivery” scenario. Overall, it can still be assumed that visual disturbance to the public, based on the values determined for both scenarios – particularly considering the average presence probability and the average concurrency of the drones – is unlikely. However, it is important to distinguish between objectively measured impacts and the perceived or felt impacts by the public. The perception of drones in urban areas may differ from the actual exposure. Initial pilot studies provide only limited insights, as they were often conducted using virtual reality and may not be directly transferable to the real world. It is currently unknown whether findings from studies on the perception and evaluation of the landscape impact of wind turbines (Nohl, 2017) can also be applied to drones.

5 Discussions and Recommendations for Action

This publication examines the opportunities and risks of unmanned aviation for parcel delivery using a passenger and freight transport model for the city region of Aachen, Germany. Two drone delivery scenarios were analysed: a “Parcel Stations” scenario, in which heavy-lift drones supply decentralised parcel stations from vertihubs, and a “Direct Delivery” scenario, in which lighter drones deliver parcels directly to customers. Based on the modelling results and a comprehensive literature review, key opportunities and risks were identified. Future European airspace concepts such as U-space (EU 2021) offer the potential to simplify and standardise drone operations and facilitate the integration of drone infrastructure into urban transport systems. However, the current legal framework poses major challenges, as regulations for the construction and operation of vertihubs are not yet adapted to drone-specific requirements. Additional legal uncertainties arise from interactions with ground traffic and state-level building regulations, leading to complex approval procedures. Regarding land use and urban integration, installing vertihubs on rooftops or repurposing existing logistics infrastructure presents opportunities to minimise land consumption and support sustainable urban development. At the same time, limited space availability, potential soil sealing and conflicts with other uses, such as photovoltaic installations, represent significant risks. Noise emissions near vertihubs may further affect residents’ quality of life. From a transport perspective, drones can reduce delivery vehicle numbers, trips and mileage, leading to minor improvements in traffic flow and safety. However, increased activity at vertihubs and parcel stations, high flight frequencies, empty return flights and coordination between air and ground traffic introduce new safety risks. Overall impacts on total urban traffic remain limited. Social acceptance is strongly influenced by concerns over safety, noise and visual disturbance. While transparent information campaigns may increase acceptance, public resistance could delay or prevent implementation. Health impacts include potential reductions in road accidents but increased noise exposure at take-off and landing sites. Economically, drone delivery can reduce daily transport costs compared to conventional delivery, but high initial investment costs, limited payloads, weather dependency and the need to maintain parallel ground-based systems constrain viability. Overall, under current conditions in Germany, large-scale drone logistics appear unrealistic and are likely to remain limited to niche applications.

Based on the results obtained, several recommendations for action can be derived for politics, administration, planning practice and the private sector to support the sustainable introduction of drone infrastructure in urban areas. A central success factor is the establishment of clear, transparent and continuous communication structures between all relevant stakeholder groups. Institutionalised coordination and traceable decision-making processes are essential to foster public trust and acceptance. An iterative and integrated planning process for vertihubs is recommended, involving specialist administrations, drone operators, research institutions and the public at an early stage. Early participation not only enhances acceptance but also enables needs-based and urban-compatible site selection. In parallel, the legal operationalisation of ground infrastructure requires careful review of existing regulations and early involvement of legal expertise to reduce uncertainties and streamline approval procedures. From an infrastructure perspective, the use of existing structures such as rooftops, parking garages or logistics hubs is advisable, as this can reduce zoning conflicts, approval times and investment costs. With regard to traffic impacts, scenarios in which drones supply decentralised parcel stations are particularly beneficial, as they reduce inner-city vehicle mileage and can positively affect traffic safety, flow and emissions. In the long term, a hybrid logistics system combining drones, electric delivery vehicles and cargo bikes is recommended to exploit modal synergies while maintaining scalability and sustainability. Although initial results suggest energy advantages of drone-based delivery, these findings should be interpreted as preliminary and require further empirical validation. Transparent and balanced communication by public institutions is crucial to inform the public about both opportunities and risks. Particular attention should be paid to noise impacts at vertihubs, where mitigation measures and low-noise technologies are essential for acceptance. Site selection should therefore carefully consider noise emissions, spatial conflicts and connectivity to existing transport systems. Overall, the introduction of urban drone systems represents a complex, interdisciplinary task. Sustainable implementation depends on coordinated, transparent and participatory processes that equally address efficiency, legal certainty and social acceptance.

6 Conclusion & Outlook

This study examines UAS, or drones, in last-mile parcel delivery through three scenarios in the region of Aachen, Germany. Results show that a scenario with drone delivery to parcel stations reduces road mileage, vehicle stops, and fleet size most effectively, while drone delivery directly to recipients increases fleet size due to limited payloads, weather constraints, and concentrated noise at vertihubs. Reduced ground mileage may lower accident risks, but UAS-ground interactions remain poorly studied. Both UAS scenarios reduce transport costs. Drone delivery to parcel stations is most cost-efficient. Social acceptance is low due to privacy, noise, and visual disturbance; noise modelling indicates local regulatory exceedances, especially at vertihubs, though mitigation is possible. Legal and regulatory frameworks are complex, involving aviation, planning, and immission laws. Effective implementation requires coordinated governance and spatial integration of vertihubs, often on rooftops to minimise land use. Overall, UAS can improve efficiency, but near-term applications in Germany are likely limited to niche, time-critical, or remote deliveries.

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