

A Spatial Assessment of eVTOLs for Emergency Medical Transport in the Brazilian Amazon

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ABSTRACT

This study investigates the applicability of electric vertical take-off and landing aircraft (eVTOLs) for emergency medical transport in the Brazilian Legal Amazon, a region characterized by vast territorial extension, limited road infrastructure, and restricted access to critical healthcare. The research estimates the population coverage potential of a selected eVTOL model and compares it to that of the Airbus H125, a conventional helicopter commonly used in aeromedical operations across Brazil. Using a Geographic Information System (GIS) spatial analyses were performed based on operational ranges, identifying populated areas within reach of hospitals equipped with adult Intensive Care Unit beds. Data from the Humanitarian Data Exchange (HDX) and Brazil's Ministry of Health supported the analysis. After filtering eVTOL models by technical feasibility and technological maturity, the Joby S4 was selected due to its extended range and load capacity. The findings indicate that while helicopters can cover a broad area from a few operational bases, eVTOLs require a larger number of strategically distributed bases to achieve similar population coverage. Our findings show that network expansion with eVTOLs is economically viable if the total operating costs per eVTOL base do not exceed roughly 3.6 times those of an equivalent helicopter base. These results support the consideration of eVTOLs as a complementary solution to improve access to emergency care in remote areas of the Amazon, contributing to the broader discussion on advanced air mobility (AAM) in complex territorial contexts.

Keywords: Air transportation; Vertical takeoff aircraft; Emergency medical services; Geographic information systems; Amazon Basin.

INTRODUCTION

The Legal Amazon is a geopolitical region of Brazil that comprises the states of Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins, covering approximately 58.9% of the national territory. Its population includes large urban centers, Indigenous and riverside communities, totaling around 29 million inhabitants, many of whom live outside these urban centers. These populations face unique challenges in accessing basic services, especially healthcare, which is concentrated in capitals and large cities. This difficulty is exacerbated by the region's vast distances and complex geography (IBGE 2023b).

Medical transportation in the Amazon faces significant logistical challenges due to its geography, with vast forests and poor land infrastructure making river and air transport the main options (Rocha *et al.* 2023; Weiss *et al.* 2020). The Amazon's transport infrastructure is often disrupted by natural disasters, such as droughts and floods, hindering access to remote communities (Marengo *et al.* 2024). Rivers are essential for transport, especially health services in isolated communities. However, boat transportation is limited by variable river conditions. The literature mentions that a well-organized river transportation system can improve the effectiveness of health services (Rocha *et al.* 2023).

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Air transport is vital for medical emergencies, improving pre-hospital rescue and reducing mortality and morbidity, as discussed by Novo *et al.* (2023) in their study on neurosurgical emergencies in the Amazon. However, air transport is expensive and depends on adequate airport infrastructure, which may be limited in the region. Studies show that populations in remote areas face long travel times to reach health facilities (Cristino *et al.* 2021; Weiss *et al.* 2020). Weiss *et al.* (2020) demonstrated that the Amazon is one of Brazil's most critical areas in terms of transport time, with many communities facing long travel times to reach emergency health services. Cristino *et al.* (2021) found that snakebite patients in 11 rural municipalities often face fragmented routes, with multiple transport changes. Challenges include limited accessibility—caused by vast distances and geographic barriers—that leads to long transfer waits and ultimately makes the journey lengthy and uncomfortable.

Electric Vertical Take-Off and Landing aircraft (eVTOLs) offer a promising solution for medical emergencies due to their ability to operate in hard-to-reach areas and significantly reduce response times. Unlike helicopters, eVTOLs offer advantages such as lower environmental impact, noise reduction, and potentially lower operational costs. Recent study suggests their potential for transporting patients and medical supplies, especially in regions with limited or nonexistent land infrastructure (Bridgelall 2024).

Although the literature highlights the benefits of aerial transport in medical emergencies, especially with helicopters and drones, as well as the potential of eVTOLs as a solution for medical transport, there is a lack of research that addresses the specific demand for emergency transport based on population presence. Most studies on transport demand are not applicable to emergencies, which can occur anywhere people are present, regardless of their predisposition to use eVTOLs. Moreover, there is a lack of detailed comparative analyses on different eVTOL models to identify which are most suitable for hard-to-reach areas with limited infrastructure and vast territorial expanses. This research fills this gap by using population data to identify demand areas and evaluating eVTOL capability in reaching these areas and directing patients to hospitals with Intensive Care Unit facilities, providing a more suitable and sustainable solution for emergency medical transport in the Amazon.

BIBLIOGRAPHIC REVIEW

Transportation in medical emergencies

Medical emergencies such as trauma, cardiac arrests, and accidents require immediate intervention to prevent severe complications or death. Rapid interventions can avoid fatal outcomes (Tranca *et al.* 2018). Efficient transportation in emergencies can be lifesaving, as reducing transport time significantly increases survival chances for critical patients, reinforcing the need for well-equipped and effective systems (Schneider *et al.* 1988; Tranca *et al.* 2018). Traffic congestion and limited access to hospitals in remote areas can delay response times, leading to severe complications or even patient death.

The literature underscores the benefits of air transport, including the use of helicopters and drones for emergencies. Abe *et al.* (2014) investigated the use of helicopters with onboard physicians in Japan, highlighting the benefits of air transport in emergencies. Beaumont *et al.* (2020) analyzed helicopter and ground ambulance services in England and concluded that helicopters provide quick access to hard-to-reach areas. Butler *et al.* (2010), through a literature review, pointed out that helicopter emergency medical services play a crucial role in decreasing response times and enhancing survival rates during emergencies, leading to better outcomes overall.

Tranca *et al.* (2018) emphasized the importance of helicopters in decreasing response times and improving survival rates during emergencies. Furthermore, air transportation is particularly advantageous in regions where ground ambulances face significant mobility challenges. Butler *et al.* (2010) emphasized the rapid transfer capabilities of air transport, allowing patients from inaccessible areas to reach higher-level trauma centers swiftly. Beaumont *et al.* (2020) reinforced this view, noting that helicopters ensure quick access to difficult-to-reach locations, especially in rural or congested areas.

Despite the high cost of air transportation, Bulger *et al.* (2012) suggested that the clinical benefits may justify the investment. Westhoff *et al.* (2003) noted that reduced transport time and improved outcomes could lead to long-term savings by decreasing intensive care needs. Similarly, Taylor *et al.* (2010) highlighted that, despite the high cost, helicopter services provide substantial benefits for survival and post-trauma quality of life. Building on these findings, the use of eVTOL presents an innovative and potentially more cost-effective solution, leveraging advanced technology to enhance medical rescue operations in hard-to-reach areas.

Use of eVTOL for medical rescue

Advanced Air Mobility (AAM) refers to the integration of modern aerial technologies, including autonomous and semiautonomous aircraft such as drones and eVTOLs, with the aim of improving transportation in urban and rural areas. AAM aims to make air transportation systems more flexible and accessible, supporting various operations, from individual and cargo transportation to essential services such as emergency medical responses (Garrow *et al.* 2021). Additionally, AAM presents an effective and cost-efficient transportation alternative in regions with significant land traffic congestion, improving access to remote or hard-to-reach areas where traditional land infrastructure is limited or nonexistent. AAM is also notable for its potential to support sustainable transportation initiatives, as many eVTOLs are designed to utilize electric or hybrid propulsion systems, resulting in lower operational and maintenance costs compared to traditional aircraft (Kasliwal *et al.* 2019).

For new technologies such as eVTOLs to be considered innovative, it is essential that they reach the market and be adopted on a large scale. As stated by Schumpeter (1934), innovation is only complete with the commercialization and widespread adoption of the developed technology. Although eVTOLs are a new technology and are not yet in operation, the literature has presented efforts to identify barriers and necessary solutions for their implementation. For example, the study by Agostinho and Bento (2022) analyzed the Brazilian regulatory framework and air traffic management system, indicating that the current infrastructure could support initial low-density operations, while regulatory adaptations may be required as operations progress.

Even though eVTOL operations remain hypothetical at this stage, based on what manufacturers propose, the literature has explored their potential applications, such as passenger transportation in metropolitan areas, airport shuttles, and emergency medical transport (Garrow *et al.* 2021).

The use of eVTOLs in medical rescue is promising due to their ability to reduce response time and reach areas with limited transportation infrastructure or difficult access. Studies such as those by Nakamoto *et al.* (2021) have concluded that the use of eVTOLs can revolutionize medical care, providing fast and effective transportation in isolated regions. Chappelle *et al.* (2018) and Goyal and Cohen (2022) suggest that these aerial vehicles can fill significant gaps in the current medical transportation system, expanding emergency services to inaccessible areas. Additionally, Sigari and Biberthaler (2021) highlight the integration of eVTOLs and drones in patient transport, medical supply delivery, and emergency teams, citing significant operational benefits despite maintenance challenges.

In the literature, the application of eVTOLs for medical rescue, compared to helicopters, has been demonstrated by Doo (2023). According to the author, eVTOL aircraft have significant advantages, such as lower operating costs due to the use of electric motors, which reduce the need for maintenance and utilize cheaper electricity than aviation fuel. Additionally, eVTOLs are regarded as safer due to multiple rotors that enhance stability. Environmentally, eVTOLs produce zero emissions during operation and generate less noise, which is beneficial for densely populated urban areas. These characteristics make eVTOLs a good fit for emergency medical services, offering a quick and efficient response, especially in areas where transportation infrastructure is limited.

Estimating demand for eVTOLs has been widely discussed in the literature, highlighting its importance for the operational and economic viability of this new mode of urban transportation. Ribeiro *et al.* (2023) investigated the feasibility of using existing infrastructure for Urban Air Mobility (UAM) operations in the São Paulo metropolitan region based on projected demand. Goyal *et al.* (2021) analyzed the demand for UAM based on mobility patterns and urban traffic, identifying potential deployment areas. Straubinger *et al.* (2021) conducted similar studies, focusing on the accessibility of vertiports from urban centers and points of interest. However, for the use of eVTOLs in medical rescues, demand analysis requires a differentiated approach. It is crucial to verify if populated regions are within the operational range of the aircraft, as demand for emergency medical services may arise anywhere there is a concentration of people (Bridgelall 2024, Espejo-Díaz *et al.* 2023). In this context, the use of Geographic Information System (GIS) technologies to map the geographical coverage of eVTOLs is essential to ensure that medical rescue infrastructure is effective and comprehensive (Rothfeld *et al.* 2021).

METHODS

This study used a GIS to assess the impact and operational feasibility of eVTOL operations in remote regions. The primary method was spatial overlap analysis, which involves creating buffer zones around specific areas, such as aerodromes, within a defined radius to evaluate influence and accessibility. The research involved two main stages: data collection, followed by processing and



analysis. Tools such as QGIS, Python routines, and Google Earth Pro enabled data manipulation and visualization, supporting the modeling of spatial relationships necessary to evaluate emergency medical service coverage and accessibility.

Longley *et al.* (2015) and Bello *et al.* (2022) offer comparable spatial analyses. In particular, Bello *et al.* (2022) mapped underserved areas in Bauchi, Nigeria, giving a detailed view of healthcare accessibility and its spatial distribution.

Data collection

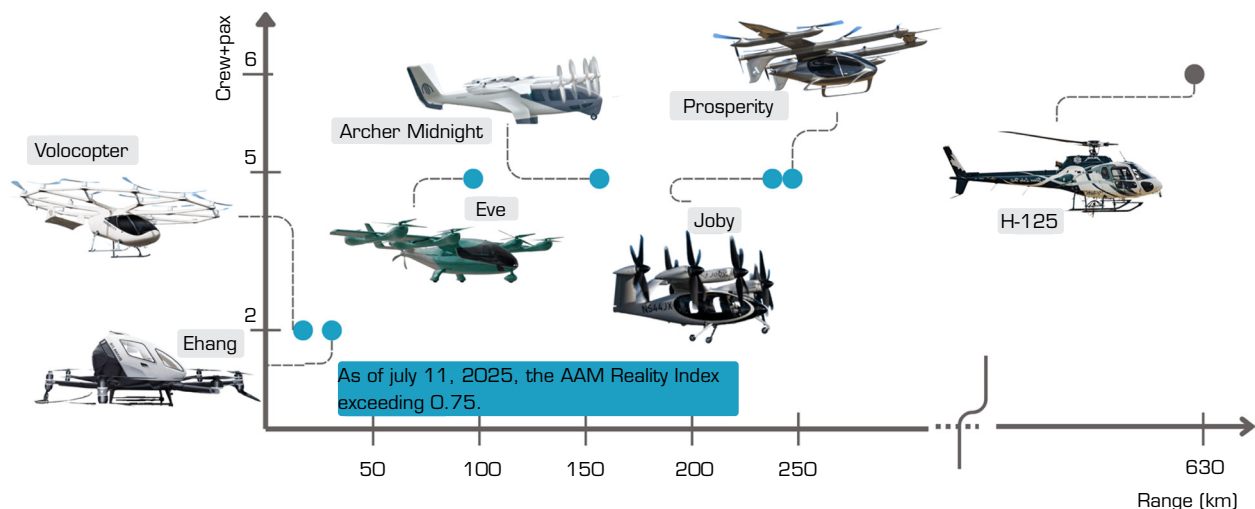
To support the spatial analysis conducted in this study, a combination of datasets was gathered, each contributing to different aspects of the feasibility evaluation of aeromedical rescue in the Legal Amazon region.

The first dataset, obtained from the Humanitarian OpenStreetMap Team (2024), provides geolocated information on populated places across Brazil. After filtering locations within the Legal Amazon, 20,478 urban settlements were identified and classified into five categories: 16,127 hamlets, 3,137 villages, 705 isolated dwellings, 459 towns, and 50 cities. For this analysis, only settlements classified as cities were selected, as they typically have more developed infrastructure and larger populations, increasing both the demand for emergency medical services and the operational feasibility of air transport.

To identify appropriate destinations for medical evacuation, hospital data were retrieved from the Brazilian Ministry of Health via the OpenDataSUS platform (Ministry of Health of Brazil 2024). The dataset includes information on all hospitals and beds in Brazil in 2024 and was filtered to include only public and philanthropic hospitals located in the selected cities and equipped with at least one adult Intensive Care Unit bed under the Unified Health System. In cities with only one eligible hospital, it was selected directly; in cities with multiple options, priority was given to those recognized as regional references for emergency and trauma care. Geographic coordinates of selected facilities were refined using Google Earth Pro to ensure precision in the spatial analysis. Further details on data filtering, geocoding, and the list of selected hospitals are available in the supplementary dataset (Silva *et al.* 2025).

The selection of aircraft focused on eVTOL models listed in the AAM Reality Index, developed by SMG Consulting (2025), which ranks projects by technological maturity and market readiness. Only eVTOLs with an AAM Reality Index above 7.5 were considered. Conventional take-off and landing aircraft and electric helicopters were excluded due to their differing infrastructure requirements and limited suitability for decentralized operations.

Operational compatibility with medical missions was further assessed through specific technical criteria. First, the number of seats was analyzed, since the cabin must accommodate one patient on a stretcher and two paramedics. Models with only two seats were excluded. Operational range was also considered, as it reflects the aircraft's potential coverage area. Figure 1 summarizes these parameters and includes the Airbus H125 helicopter, widely used by Brazil's Águia rescue program, as a conventional benchmark.



Source: Adapted from Ehang (2025), Volocopter (2025), Airbus (2025), Archer Aviation (2025), Autoflight (2025), Eve Air Mobility (2025), and Joby Aviation (2021).

Figure 1. Operational range and seating capacity of selected eVTOL aircraft.

Payload capacity was an additional criterion. Aircraft unable to carry at least 400 kg were excluded, as this is the minimum estimated requirement to transport one patient, two paramedics, and essential medical equipment, totaling approximately 365 kg.

After applying all filters, three eVTOLs were identified as suitable for this study: Eve, Archer Midnight, and Joby S4. Among them, the Joby S4 was selected for spatial coverage analysis due to its superior operational range, offering broader reach in emergency scenarios.

To complement the spatial analysis, population data were incorporated from the HDX, part of the Data for Good initiative (HDX 2019). The source raster offers 30×30 m population estimates for all of Brazil, but to cut processing time while still meeting our study's resolution needs we resampled it to a 300×300 m grid. Afterward, the dataset was clipped to the Legal Amazon, allowing us to estimate the total population within the coverage areas of the Joby S4 and the H125 and to compare each aircraft's potential to reach communities requiring urgent medical care.

Assumptions

This study assumes that, under the current Brazilian regulatory framework, flights over Indigenous lands and conservation units in the Legal Amazon face no specific restrictions. Analysis of regulated airspace from data on GeoAISWEB (DECEA 2024) portal shows that these areas are not classified as segregated, prohibited, restricted, or danger zones, so routine overflights are permitted. If AAM scales up in the future, new constraints could emerge and affect our findings. For routine operations or landings within these territories, prior authorization is still required from competent agencies (e.g., the National Indigenous People Foundation or Chico Mendes Institute for Biodiversity Conservation). In medical emergencies, aircraft may land and evacuate patients without prior authorization, as such operations are exceptional, humanitarian, and in the public interest.

Data processing and analysis

The spatial analysis conducted in this study aimed to estimate the population coverage potential of two aircraft models, Joby S4 and Airbus H125, within the Legal Amazon. For both models, the coverage radius was defined as half of their maximum range, simulating complete round-trip rescue missions without requiring recharging or refueling during the operation. This assumption reflects the current lack of charging infrastructure or battery-swapping systems for the selected eVTOLs. As a result, a 315 km radius was considered for the H125 (range: 630 km) and 120 km for the Joby S4 (range: 240 km).

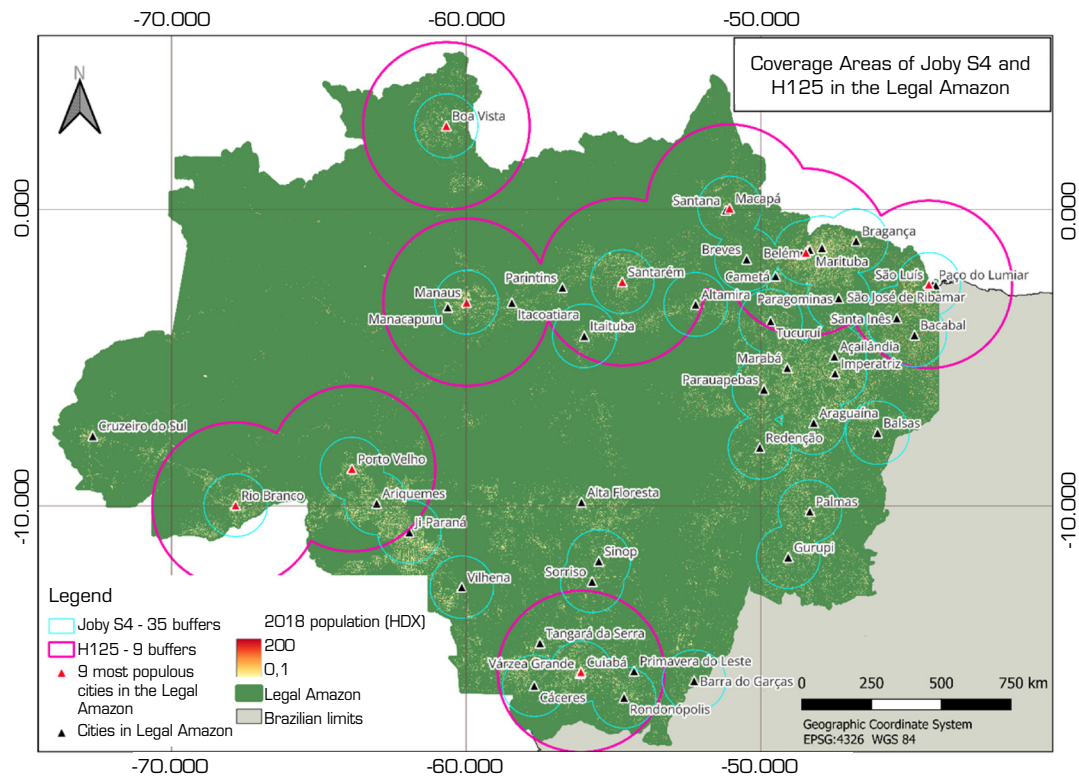
The first step involved selecting nine operational bases corresponding to the most populous cities in the Legal Amazon, according to the 2022 Brazilian Census (IBGE 2023a). The selected cities were: Manaus (AM), Belém (PA), São Luís (MA), Macapá (AP), Porto Velho (RO), Rio Branco (AC), Boa Vista (RR), Cuiabá (MT), and Santarém (PA). A coverage analysis was initially carried out using these nine cities as H125 bases. The same configuration was then applied to the Joby S4, allowing for a direct comparison between the two aircraft under equivalent spatial conditions.

In the next phase, additional cities were progressively added to evaluate how the expansion of eVTOL bases could enhance population coverage. The selection was based on city population (IBGE 2023a), and cities were grouped into configurations with 12, 15, 18, 24, 27, 30, 33, and 35 locations. To avoid spatial redundancy, cities located less than 20 km apart were excluded from the same group. For each configuration, 120 km coverage buffers were generated, and the population within those areas was estimated using high-resolution raster data from the HDX. Figure 2 presents the coverage areas resulting from the nine H125 bases and the 35 Joby S4 bases.

At each step, the coverage obtained by the Joby S4 was compared to the baseline coverage of the H125 with 9 fixed bases. This enabled an evaluation of how the expansion of operational points could progressively improve the eVTOL's performance in relation to the conventional helicopter.

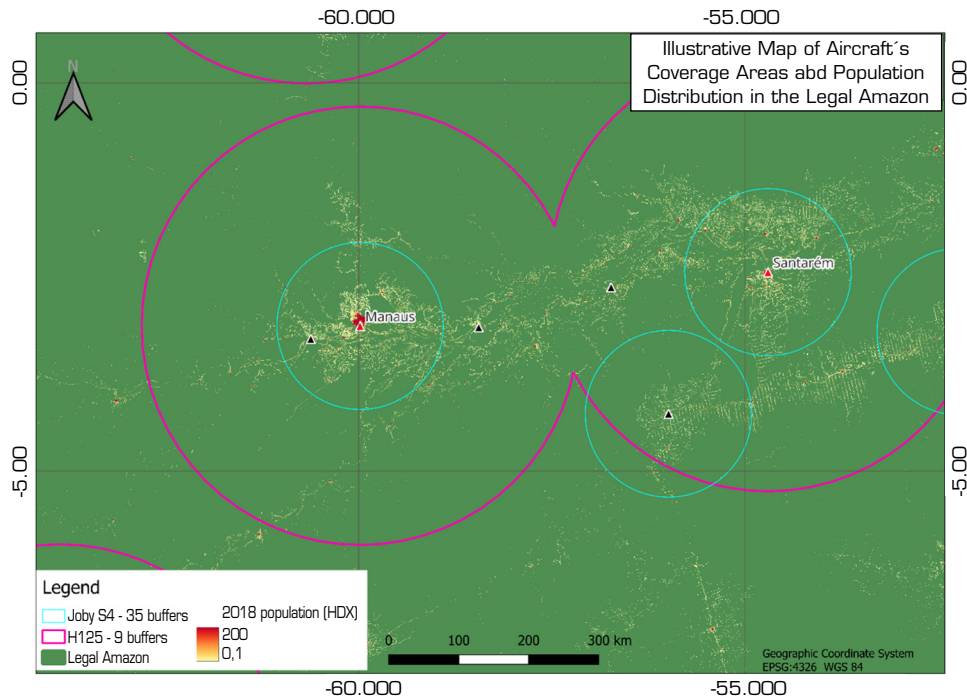
Finally, an assessment was conducted to determine the proportion of the Legal Amazon's total population covered by each aircraft. For this, the population reached by the H125 with 9 bases and by the Joby S4 with 35 bases was calculated and compared to the region's total population, as estimated by the HDX. This comparison aimed to quantify the overall effectiveness of each model in responding to medical transport needs across the region.

To better illustrate how the spatial analysis was conducted, a zoomed-in example showing the overlap of aircraft coverage areas with HDX population data is presented in Fig. 3.



Source: Adapted from HDX (2019), IBGE (2023b), Joby Aviation (2021), and Airbus (2025).

Figure 2. Joby S4 and H125 coverage areas.



Source: Adapted from HDX (2019), IBGE (2023b), Joby Aviation (2021), and Airbus (2025).

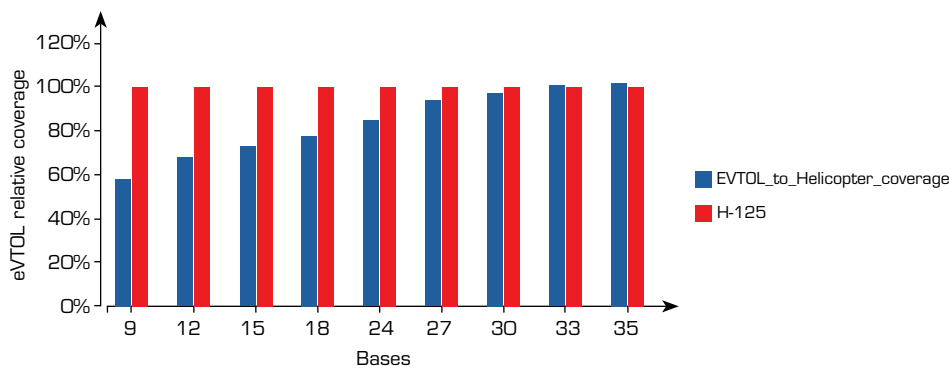
Figure 3. Example of coverage areas for the Airbus H125 and Joby S4 in the Legal Amazon, overlaid with HDX population data.

RESULTS AND ANALYSIS

The spatial analysis compares the capacity of the Joby S4 eVTOL to serve populations in need of emergency medical transport with that of a conventional helicopter. For reference, we used the Airbus H125, widely employed in aeromedical services across Brazil, as a benchmark. This comparison illustrates how aircraft specifications and the strategy used to distribute operational bases affect coverage in a region characterized by long distances and limited infrastructure.

Using nine operational bases located in the most populous cities of the Legal Amazon, the H125 is capable of reaching approximately 71% of the region's population, based on our calculations using a subset of the population estimates provided by HDX (2019). When the same nine-base configuration is applied to the Joby S4, population coverage is considerably lower due to its shorter operational range.

To enhance Joby S4 coverage, additional bases were gradually included, prioritizing cities by population size. This incremental approach significantly increased service coverage: with operations expanded to 35 cities, including all state capitals and major urban centers, Joby S4 is able to reach around 78% of the regional population. This contrast is visually presented in Fig. 4.



Source: Elaborated by the authors.

Figure 4. Comparative population coverage of the H125 and Joby S4 aircraft across different base configurations in the Legal Amazon.

While H125 achieves this level of coverage with only nine bases, Joby S4 requires 33. The primary factor behind this difference is the aircrafts' range. From an economic perspective, deploying eVTOLs becomes advantageous only when the total cost of installing and maintaining a base for the H125 is more than 3.6 times higher than for a Joby S4 base. This value serves as a useful reference for evaluating the cost-effectiveness of each aircraft under varying deployment strategies.

These results are consistent with prior studies on the role of air transport in improving access to emergency care in remote regions (Schneider *et al.* 1988; Tranca *et al.* 2018). They also contribute to ongoing discussions about the practical use of eVTOLs in areas with long distances and limited infrastructure, such as the Legal Amazon (Doo 2023; Sigari and Biberthaler 2021). The inclusion of spatial population data reinforces the relevance of this analysis by linking aircraft performance to actual service potential (Beaumont *et al.* 2020; Galvagno Jr. *et al.* 2012).

Manufacturers of eVTOLs estimate significantly lower operating costs compared to conventional helicopters. Eve Air Mobility (2025) claims that its model will have a per-seat cost more than six times lower than that of a helicopter. Archer projects initial costs between US\$ 4 and US\$ 5 per passenger-mile, with a target of reducing it to US\$ 1, while helicopters typically operate at around US\$ 10 per passenger-mile (Syme 2023). Joby, in turn, anticipates initial fares around US\$ 5 per mile, with gradual reduction over time (eVTOL Insights 2024). In the context of the Brazilian Legal Amazon, this study found that approximately 3.6 times more Joby S4 eVTOL bases would be required to match the territorial coverage of H125 bases. Although manufacturers' cost estimates suggest this ratio could be viable, they remain projections not yet validated by real-world commercial operations.

CONCLUSION

This study assessed the applicability of eVTOLs to emergency medical transport in the Legal Amazon, focusing on their population coverage potential. Among the aircraft identified as most mature and suitable for medical rescue operations, the Joby S4 was selected for spatial analysis due to its superior range. Its coverage was evaluated using population data from the HDX and compared to that of the Airbus H125, a helicopter widely used in Brazil for urgent missions. The analysis showed that while the H125 can cover a wide area from a limited number of bases, the Joby S4 requires a greater number of strategically located bases to achieve similar results. From this comparison, it was possible to estimate the ratio of operational bases needed and discuss, in general terms, under what conditions eVTOLs could become a more viable alternative in economic and logistical terms.

Some limitations should be acknowledged. The analysis assumes that all areas within the coverage radius are accessible for landing, which may not apply in regions with dense forest, steep terrain, or lack of suitable open spaces. These geographic and environmental barriers can limit the operations of eVTOLs in several parts of the Amazon. Additionally, the study does not include flight route planning, availability of ground support, or meteorological variability, all of which may influence the feasibility of real-world missions. In addition, although the aircraft selected for this study are among the most advanced in terms of development and certification, they have not yet entered into full operation. Therefore, performance data, such as maximum range, payload capacity, and turnaround time, are based on manufacturer specifications and may not reflect future real-world capabilities. It is also not guaranteed that all selected models will reach the market.

Future research could incorporate terrain data, land cover maps, and realistic models of landing feasibility to refine spatial coverage estimates. Studies could also explore seasonal effects on access (e.g., flooding or drought), the integration of drones for support missions, and hybrid models that combine eVTOLs with existing helicopter services. In parallel, further investigation into regulatory readiness, public acceptance, and the costs of infrastructure adaptation will be essential for guiding implementation strategies in remote areas.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Souza GO; Silva EJ; Caetano M; **Methodology:** Souza GO; Silva EJ; **Software:** Souza GO; Silva EJ; **Formal analysis:** Souza GO; Silva EJ; Caetano M; **Investigation:** Souza GO; **Data Curation:** Souza GO; Silva EJ; **Writing (original draft):** Souza GO; **Writing (review & editing):** Silva EJ; Caetano M; **Supervision:** Caetano M; **Project administration:** Caetano M; **Final approval:** Souza GO.

DATA AVAILABILITY STATEMENT

The complementary data are available in the Zenodo repository: <https://doi.org/10.5281/zenodo.16955477>

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