Article

Spatial Analysis of Advanced Air Mobility in Rural Healthcare Logistics

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Abstract: The transportation of patients in emergency medical situations, particularly in rural areas, often faces significant challenges due to long travel distances and limited access to healthcare facilities. These challenges can result in critical delays in medical care, adversely affecting patient outcomes. Addressing this issue is essential for improving survival rates and health outcomes in underserved regions. This study explored the potential of advanced air mobility to enhance emergency medical services by reducing patient transport times through the strategic placement of vertiports. Using North Dakota as a case study, the research developed a GIS-based optimization workflow to identify optimal vertiport locations that maximize time savings. The study highlighted the benefits of strategic vertiport placement at existing airports and hospital heliports to minimize community disruption and leverage underutilized infrastructure. A key finding was that the optimized mixed-mode routes could reduce patient transport times by up to 21.8 min compared with drive-only routes, significantly impacting emergency response efficiency. Additionally, the study revealed that more than 45% of the populated areas experienced reduced ground travel times due to the integration of vertiports, highlighting the strategic importance of vertiport placement in optimizing emergency medical services. The research also demonstrated the replicability of the GIS-based optimization model for other regions, offering valuable insights for policymakers and stakeholders in enhancing EMS through advanced air mobility solutions.

Keywords: advanced air mobility; air ambulance services; eVTOL; GIS-based optimization; ground–air integration; uncrewed aircraft system; rural healthcare; strategic vertiport placement

1. Introduction

Advanced air mobility (AAM) represents a transformative approach to enhancing transportation efficiency and accessibility through the use of new aviation technologies such as uncrewed aerial vehicles (UAVs) and electric vertical takeoff and landing (eVTOL) aircraft that can transport both people and heavy cargo. This research investigated the deployment of AAM to improve emergency medical services (EMS), particularly in rural areas where traditional ground transportation is often inadequate. The strategic placement of vertiports, which are designated sites for eVTOL landing and takeoff, plays a critical role in optimizing the efficiency and feasibility of aerial transportation networks.

The significance of this research lies in its potential to address critical delays in medical care in underserved regions to improve health outcomes and survival rates. AAM offers multifaceted benefits, including the rapid transport of patients and medical supplies, air ambulance services, and the delivery of critical supplies to remote locations. These capabilities are particularly valuable in emergency scenarios where time is of the essence [1,2].

Despite the promising benefits of AAM, several challenges persist, including limitations in battery technology, regulatory hurdles, and public acceptance [3]. However, analysts suggest that demonstrating the practical benefits of AAM through early use cases, such as emergency response and aeromedical transport, can help overcome these barriers and build public trust [4]. The goal of this study was to assess the potential benefits of

AAM in a rural state by optimally placing vertiports to reduce patient transport times to hospitals, focusing on North Dakota due to its unique federally approved beyond visual line-of-sight (BVLOS) operations across the entire state [5]. The Federal Aviation Administration (FAA), which is an operating mode of the U.S. Department of Transportation, granted the BVLOS approval.

This research contributes to the existing body of knowledge by developing a GIS-based optimization workflow to identify optimal vertiport locations that maximize time savings. Previous studies have demonstrated the potential of AAM to revolutionize EMS, especially in rural and underserved areas with limited ground transportation options [6,7]. Researchers have highlighted the effectiveness of drones in delivering human organs, blood products, and time-critical medical interventions, highlighting the speed and reliability of aerial delivery systems [8–11].

Scholars have widely applied traditional optimization models such as the traveling salesman problem (TSP) and the vehicle routing problem (VRP) to minimize travel times and costs in medical supply chains. The advent of AAM introduces new dimensions to these optimization problems, necessitating novel models and algorithms [12–15]. The strategic placement of vertiports is critical to the success of AAM in healthcare logistics, with location playing a more significant role than the number of vertiports [16–18].

However, regulatory frameworks for UAV and eVTOL operations are still evolving, with safety and air traffic management being primary concerns [3,19]. Battery technology remains a challenge, although manufacturers are making continuous improvements [20]. Technological advancements such as reduced charge times, increased operational range, and battery swapping could enhance the viability of eVTOL aircraft [4]. The integration of AAM into existing healthcare systems requires significant investments in infrastructure and technology, emphasizing the importance of public–private partnerships [21].

The GIS-based optimization workflow developed in this study offers a replicable model for other regions and contributes to the broader understanding of AAM's role in enhancing EMS. While this study utilized data specific to North Dakota, the author designed the GIS-based optimization workflow to be adaptable to other regions. By leveraging locally available datasets, such as those from local transportation authorities, health departments, and geospatial data providers, others can implement the methodology in diverse geographic and socio-economic contexts. The structure of this paper is as follows: Section 2 reviews the literature on AAM, focusing on air ambulance services and spatial optimization methods. Section 3 describes the data sources and GIS optimization workflow. Section 4 presents the statistical findings on time savings. Section 5 discusses the results and implications for stakeholders. Section 6 concludes the research and suggests future work.

2. Literature Review

This section provides an in-depth review of the existing literature on AAM, focusing on its potential and challenges specifically related to EMS. While the introduction section outlined the broader context and significance of AAM, this section offers a detailed examination of previous studies, methodologies, and findings that form the basis for this research. By exploring various optimization models, case studies, and empirical evidence, this section highlights the critical insights and knowledge gaps that this study aimed to address.

The recent literature has extensively explored the potential of AAM to revolutionize EMS, highlighting both the opportunities and challenges associated with its deployment. The potential is especially strong in areas with limited access to healthcare facilities, such as rural and tribal areas. UAVs and eVTOL aircraft can significantly reduce the time required to transport patients and medical supplies, which is critical in life-threatening situations such as out-of-hospital cardiac arrests [6,7]. The rapid delivery capabilities of drones have been particularly beneficial for transporting human organs, blood products, and emergency medical equipment [8–10]. For instance, Sigari and Biberthaler (2021) found that aerial

delivery systems could potentially reduce response times and improve survival rates for cardiac arrest patients by overcoming the limitations of ground transportation [11].

The strategic placement of vertiports is crucial to maximizing the benefits of AAM. Optimization models such as the traveling salesman problem (TSP) and the vehicle routing problem (VRP) have been adapted to include mixed-mode transportation solutions, integrating ground and air travel to minimize patient transport times [12,13]. Research by Zhou et al. (2020) and Pachayappan and Sundarakani (2023) has developed mixed-integer linear programming (MILP) models to optimize the routing and placement of drones and vertiports, ensuring efficient coverage and minimal travel times [14,15].

The literature emphasizes that the location of vertiports is more critical than the number of sites. Studies have used various spatial analysis techniques to identify optimal vertiport locations based on factors such as population density, accessibility, and potential demand for EMS [16–18]. These analyses aimed to balance operational efficiency with societal benefits, ensuring that AAM infrastructure is both effective and minimally disruptive.

Despite the promising potential of AAM, several challenges remain. Regulatory frameworks for UAV and eVTOL operations are still evolving, with safety, air traffic management, and public acceptance being primary concerns [3,19]. Battery technology, although continuously improving, still presents limitations in terms of range and reliability, particularly for critical air ambulance operations [4,20]. Hence, technological advancements such as reduced charge times and battery swapping systems could enhance the viability of eVTOL aircraft for EMS. Public–private partnerships and substantial investments in infrastructure and technology are essential to overcoming these challenges and realizing AAM's full potential [21].

A notable gap remains in the literature concerning comprehensive studies on the practical implementation of AAM for EMS. While many studies focus on the theoretical and technical aspects of AAM, there is a lack of empirical research that evaluates actual deployments and their impacts on EMS [22]. In particular, there is a lack of case studies and pilot programs to assess the feasibility, efficiency, and public acceptance of AAM in various settings.

3. Methodology

Studies found that many airports were underutilized, with only 10% of the more than 5000 public airports in the United States providing scheduled air service [23]. Therefore, this study focused on identifying public airports as candidates for vertiport installations. The subsections that follow provide details about the utilized data and describe the GIS and optimization workflow, including the details of the various applied procedures.

3.1. Data Sources

Table 1 provides the details of the datasets utilized in this study. The GIS data representing roads, populated places, hospitals, and airports were from publicly available datasets that various government and state agencies maintain as indicated. In particular, the Highway Performance Monitoring System (HPMS) data reflected the extent, condition, performance, use, and operating characteristics of U.S. roadways [24]. The HPMS data were part of the U.S. Department of Transportation (USDOT), Bureau of Transportation Statistics (BTS), and National Transportation Atlas Database (NTAD), which the U.S. Federal Highway Administration (FHWA) compiles annually to support and inform highway planning, policy making, and decision making at the national, state, and local levels. The airport database contained information on the physical and operational characteristics of official operational aerodromes in the United States, derived from the National Airspace System resource, "Aeronautical Data and Products" of the Federal Aviation Administration (FAA) [25]. AirNav.com provided a list of N.D. heliports by filtering updated airport information provided the by FAA [26].

The places dataset contained annually updated populated areas that included both incorporated places and census-designated places identified by the U.S. Census Bureau [27]. ESRI, a developer of GIS software (Spatial Reference 102100 (3857)), sourced the geography from the U.S. Census Bureau 2020 TIGER Public Law 94–171 dataset to add a detailed coastline [28]. The U.S. Homeland Infrastructure Foundation-Level Data (HIFLD), managed by the U.S. Geospatial Management Office, provided a dataset of U.S. tribal lands. The largest tribal nations by land area were Fort Berthold, Spirit Lake, Standing Rock, Turtle Mountain, and Lake Traverse. According to the North Dakota Indian Affairs Commission, there are 31,329 Native Americans living in North Dakota, accounting for 4.9% of the total population [29]. The HIFLD dataset also contained information about hospitals, which are part of its geospatial data on U.S. critical infrastructure [30]. Although the data used in this study were specific to North Dakota, the same methodology is applicable to other locations by extracting the corresponding data from the national datasets of the HPMS, BTS, ESRI, and HIFLD. Analysts can then combine the extracted data with other local data obtained from regional transportation and health departments.

Table 1. Dataset details.

Data	Description	Content	Source
Roads	Shapefile of lines representing ND road network geometry.	Extracted 349,585 road segments from the ND layer of the HPMS geodatabase containing layers of individual state road segments.	HPMS [24]
Airports	Shapefile of points representing airports in the USA.	Extracted 281 ND airports of 19,850 from the U.S. Department of Transportation (USDOT) Bureau of Transportation Statistics (BTS) dataset.	BTS [25]
Heliports	A list of heliports in ND.	Augmented the HIFLD hospital data with heliport information.	AirNav [26]
Places	Shapefile of polygons representing populated places in the USA.	Extracted 406 ND places of 31,616 in the ESRI USA Census Populated Places database.	ESRI [28]
Reservations	Shapefile of polygons representing Native American reservations.	Extracted all the ND locations among 835 U.S. locations in the HIFLD dataset.	HIFLD [30]
Hospitals	Shapefile of points representing hospitals in the USA.	Extracted 62 ND hospitals among 8013 in the US HIFLD and reconciled them with the North Dakota Medical Association (NDMA) dataset.	HIFLD [30] NDMA [31]

3.2. GIS and Optimization

The author developed the following methods and procedures specifically for this study. Figure 1 illustrates the GIS and optimization workflow with the procedures and their interactions. This figure helps to visualize the comprehensive workflow used for the GIS-based optimization. Each step, from data preparation to optimization and verification, ensured the accuracy and efficiency of the model. The dissolve procedure, centroid creation, and snapping geometries were foundational steps that ensured the accuracy and connectivity of all points within the network. The OD matrix calculation and optimization steps were critical for determining the most efficient routes. The workflow utilized version 3.34.6 of the QGIS software and Python code to implement all procedures shown in the workflow [32].
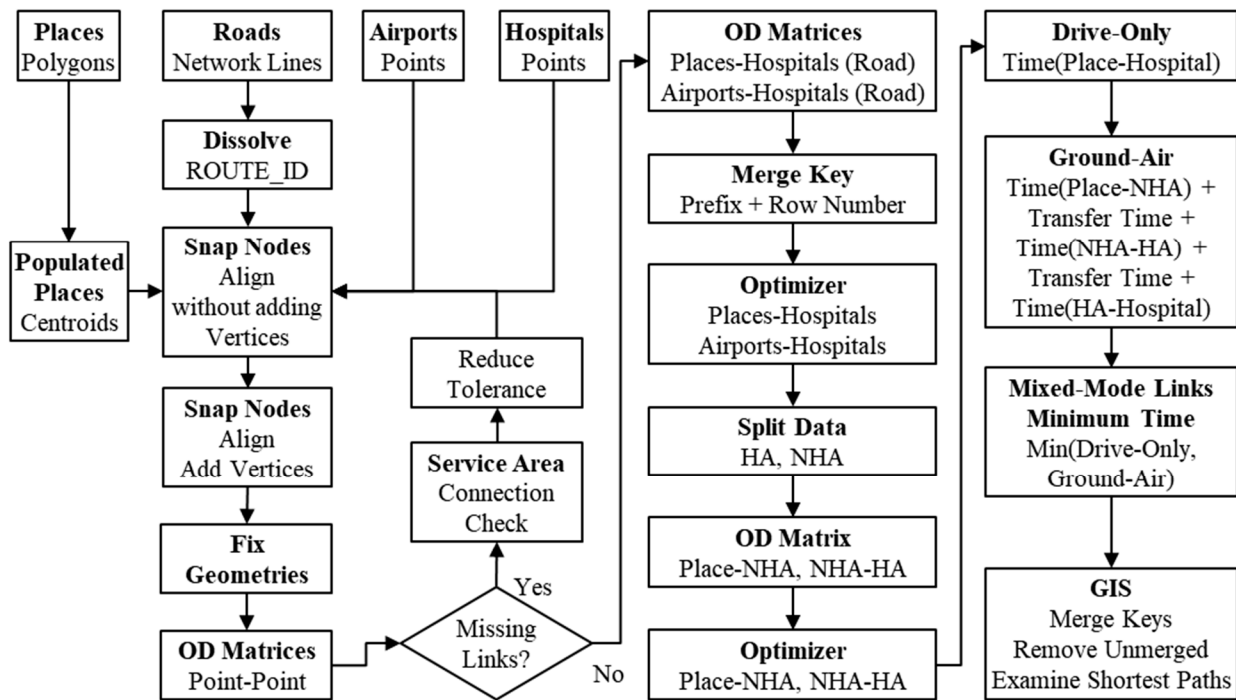
Figure 1. GIS and optimization workflow.

To reduce the data size, the GIS dissolve procedure combined line objects representing the same road based on the identifier ROUTE_ID. This procedure reduced the number of GIS objects from 349,585 to 23,718, reducing the processing time by a factor of 15 without losing any of the required network information. The centroids procedure created a point representation from the polygons representing populated places to designate a standardized network access location for the shortest path calculations. All trips originated from points representing populated places and concluded at points representing hospital locations on the road network. The airport points represented airport access locations on the road network. These airports served as transfer points to vertiports that reduced the total travel time to a hospital over the drive-only alternative.

All points must connect to the road network within some distance tolerance to assure that a GIS procedure can calculate the shortest path between any two points on the network. The GIS "snap geometries to layer" procedure assured this condition with several iterations. The first was to remove superfluous line splits in the network geometry by merging them and removing any small connectivity gap errors along road segments. The snap geometries procedure achieved this by using the "prefer aligning nodes, don't insert new vertices" option, followed by a GIS "fix geometries" procedure. The snap geometries procedure also moved all points representing places, hospitals, and airports to touch the nearest road segment. The "prefer aligning nodes, insert extra vertices where required" option of the geometry snapping procedure ensured network connectivity for all nodes that represented valid road intersections.

The "QGIS Network Analysis Toolbox (QNEAT3): OD Matrix from Layers as Lines" procedure calculated a distance matrix of the shortest paths between points. This step ensured connectivity between all points on the network, enabling the computation of origin–destination (OD) matrices for various routes. The workflow checked for any missing connections between nodes, indicated by a "NULL" distance for those entries. This could occur if the distance tolerance setting for computing distances along paths was too large. Reducing the distance tolerance increased the accuracy of path following but also increased the computational cost. Hence, the tradeoff involved heuristics with the GIS user adjusting tolerances, running a GIS service area check from the isolated points, and repeating the alignment of points until the distance matrix had no null distances except for the distances

between points and itself. The optimizer then assigned places to hospitals and hospitals to airports to minimize overall drive time. This assignment process involved several iterations of snapping geometries to the road network, merging lines, and fixing any connectivity issues.

After verifying that the network complied with all the point-to-point connectivity checks, the user could compute the required origin–destination (OD) matrices of places to hospitals and airports to hospitals along the shortest paths on the road network. Adding a unique key to each row aided in merging the optimizer results back into the GIS tables to visualize the selected routes. The final optimization assigned places to hospitals that minimized the overall drive time as follows:

I: set of places, indexed by *i*.

J: set of hospitals, indexed by *j*.

c_{ij}: total cost (road network distance) of assigning place *i* to hospital *j*.

x_{ij}: binary decision variable that equals 1 if the optimizer assigns place *i* to hospital *j* and 0 otherwise. Hence, the optimization problem is to minimize the total assignment cost as follows:

Minimize:

$$C = \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} \tag{1}$$

Subject to:

$$\sum_{j \in J} x_{ij} = 1 \quad \forall i \in I \tag{2}$$

The constraint indicated after "Subject to:" ensures that the optimizer assigns each town to exactly one hospital. The same formulation assigned each hospital to exactly one airport. The workflow implemented the above equations using the PuLP library in Python Version 2.8.0, which is a linear programming tool used for optimization problems. The author formulated the optimization problem to minimize the total assignment cost of patient transport routes. The author translated the variables and constraints defined in the above equations into the syntax required by the PuLP tool to solve the assignment problem efficiently. The OD matrices provided the input data for the optimization model. The decision variables were binary, indicating whether the optimizer assigned a place *i* to a hospital *j*. The objective function aimed to minimize the total cost *C*, defined as the sum of the products of the binary variables and the corresponding travel costs c_{ij}. The constraints ensured that the optimizer assigned each place to exactly one hospital. After defining the model, the PuLP solver found the optimal assignment of places to hospitals, minimizing the overall travel distance.

The "split data" procedure identified a hospital airport (HA) as one assigned by the optimizer and the remainder as non-hospital airports (NHAs). An HA assured that vertiports could be accessible close to hospitals that could not accommodate them directly on their facilities. The GIS then computed the OD matrix for places to NHAs, and the same optimization formulation above assigned each town to exactly one NHA.

The "drive-only" procedure computed a drive time in minutes between the places and their assigned hospitals. This calculation utilized the average speed limit of 40 mph derived from the HPMS dataset. Similarly, the "ground–air" procedure computed the trip time in minutes based on driving to an NHA, transferring the patient to the aircraft, flying to an HA, transferring the patient to a ground vehicle, and driving to the assigned hospital. The flight duration was based on a common speed of 100 mph that Bridgelall et al. (2023) reported for heavy-lift drones that were best suited for this type of application [33]. This study estimated a five-minute nominal transfer time between ground and air vehicles to include time for preparing connections to medication and vital sign equipment, moving the patient between vehicles, conducting safety checks, completing pre-flight procedures, and transitioning between vertical and horizontal flights.

The "mixed-mode links minimum time" procedure selected the shortest-duration trip among the drive-only and ground–air alternatives as the shortest-duration solution. The

GIS procedure "join attributes by field value" then merged the results with the respective OD matrices by using the merge keys. Keeping only the merged values displayed the optimized mixed-mode routes consisting of either the drive-only or ground–air routes, whichever was the shorter duration.

4. Results

The following subsections present the results of the GIS route optimization, their trip time distributions, vertiport site selection, the potential impact of locating vertiports at hospital heliports, and potential savings in ground travel times to avoid difficult road situations.

4.1. Optimized Routes

Figure 2 shows the optimized routes, which are the minimum durations of either the drive-only or ground–air routes from places to their assigned hospitals. The light gray lines represent all the roads in the state. As indicated by the legend, the solid black lines represent the optimized drive-only routes along the road network. For the ground–air paths, the solid red lines represent the drive portions from places to NHAs or from HAs to hospitals, and the dotted red lines represent the flight path segment from NHAs to HAs. The labeled boxes with arrows pointing to airports are those proposed for vertiport installations, based on a ranking analysis that follows later. The optimization selected these locations based on their potential to significantly reduce travel times, particularly for remote and underserved areas. The pink areas indicate ND tribal nations, emphasizing the inclusivity of the proposed solution.

4.2. Time Distributions

Figure 3 compares the distributions of drive-only trip times (base case without air travel) with those of the optimized mixed-mode (minimum time of drive-only or ground–air) trip times. The inset box of each distribution chart on the left of the figure summarizes key statistics such as the mean, median, standard deviation (STD), minimum (Min), and maximum (Max) values. The chart on the right of each figure is a box plot that provides a visualization of the interquartile range, median value, data extent, and outliers. The results suggested that although the mean trip time for the optimized mixed-mode routes was only $33 - 31.3 = 1.7$ min shorter than the optimized drive-only routes, the maximum time savings was $102.7 - 80.9 = 21.8$ min. That is, the optimized mixed-mode routes could reduce some of the extreme drive durations of the optimized drive-only routes, which were fewer than 10 places. This suggested that only a few places would benefit from reduced trip times to hospitals by installing vertiports. These results demonstrated that while the average time savings for optimized mixed-mode routes were modest, the maximum time savings could be substantial, reducing extreme drive durations by up to 21.8 min. This reduction is critical for emergency response efficiency.

Figure 4 shows the distribution of time saved by taking ground–air trips instead of drive-only trips. The negative values indicate where drive-only trips were shorter than ground–air trips. The statistics shown in the chart inset indicate that drive-only trips will be, on average, 32.1 min shorter than ground–air trips. This chart also indicates that ground–air trips can provide time savings for only a small number of places at the upper extreme of the distribution. Hence, airports near those locations would be candidates for vertiport installations. These results show the potential time savings for specific locations, highlighting the importance of targeted vertiport placement.
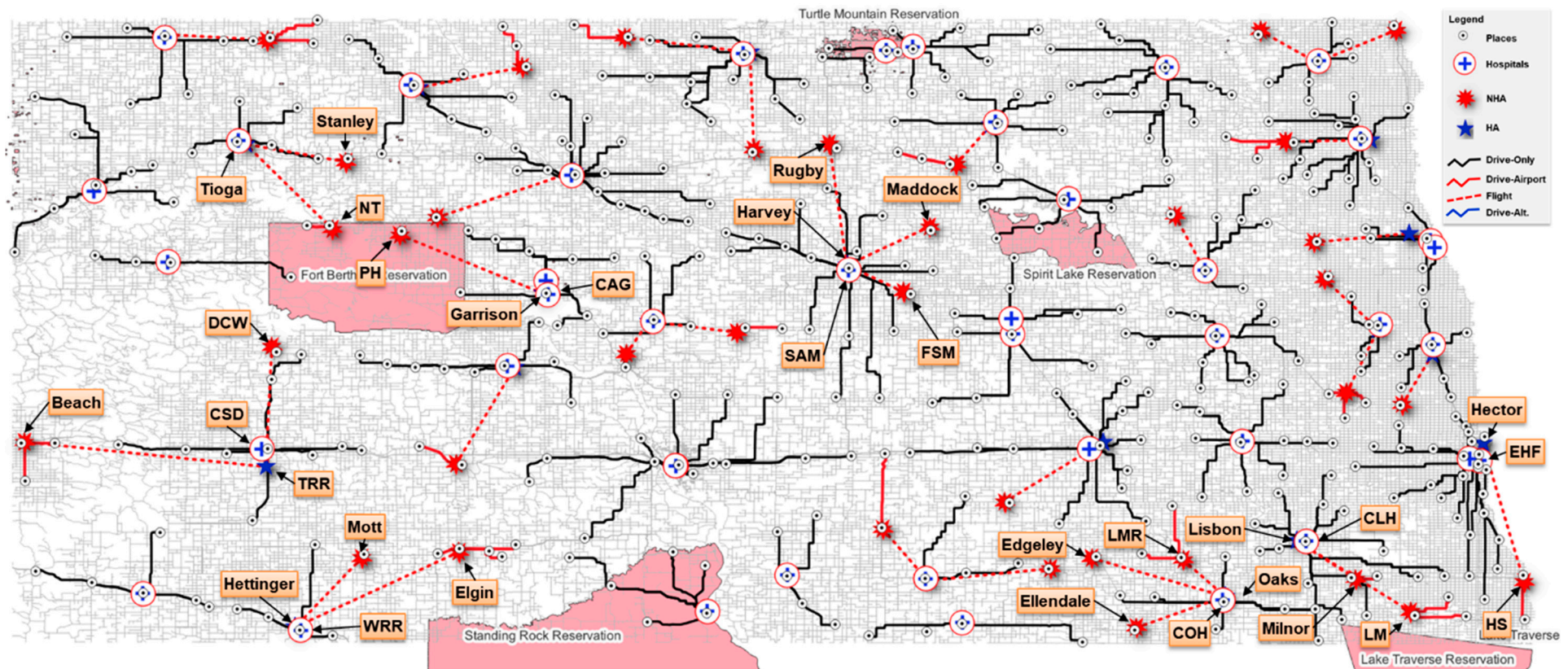
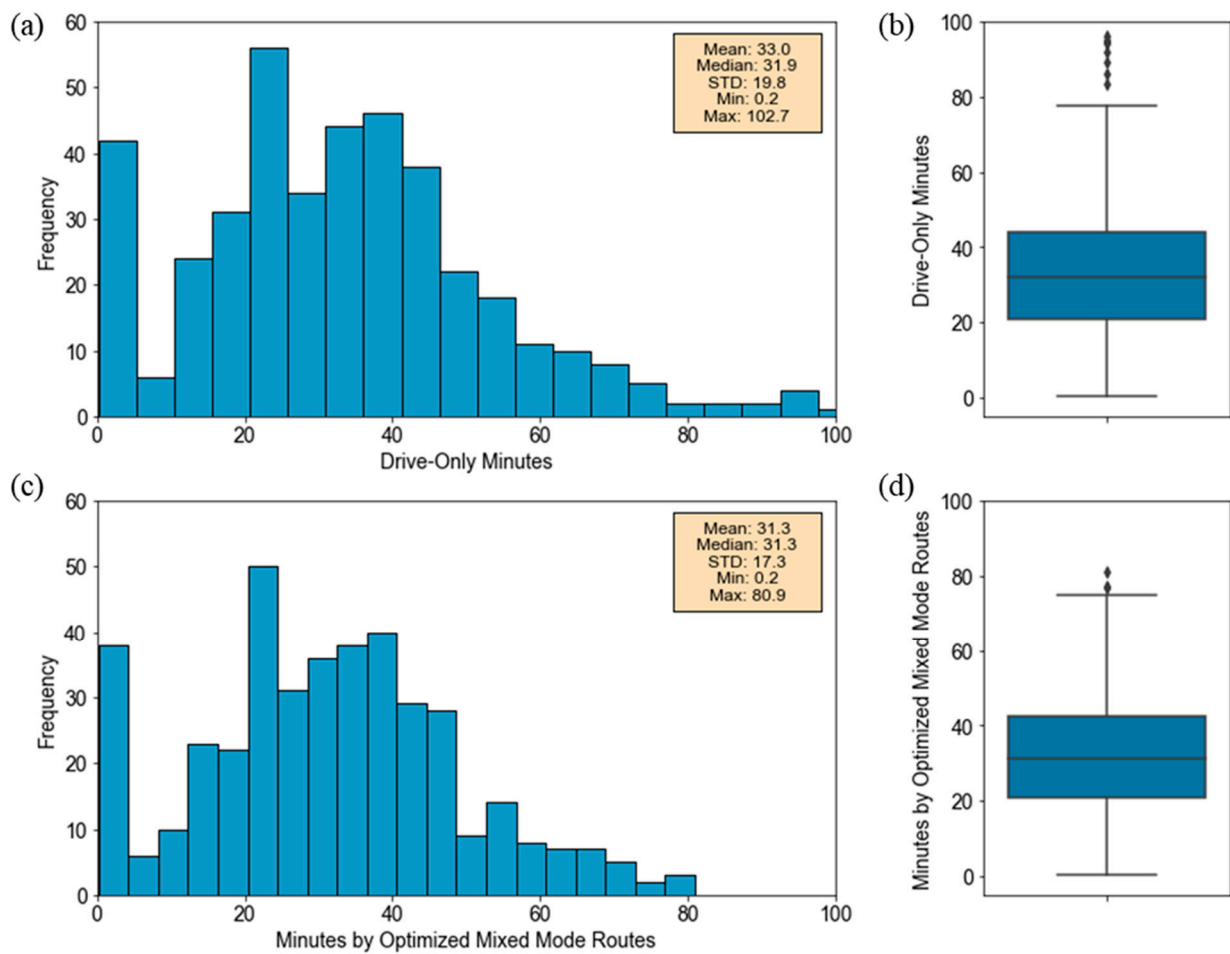**Figure 2.** Optimized routes for shortest-duration travel to a hospital.

Figure 3. Distributions of drive-only trip times (**a**,**b**) and the optimized mixed-mode trip times (**c**,**d**).
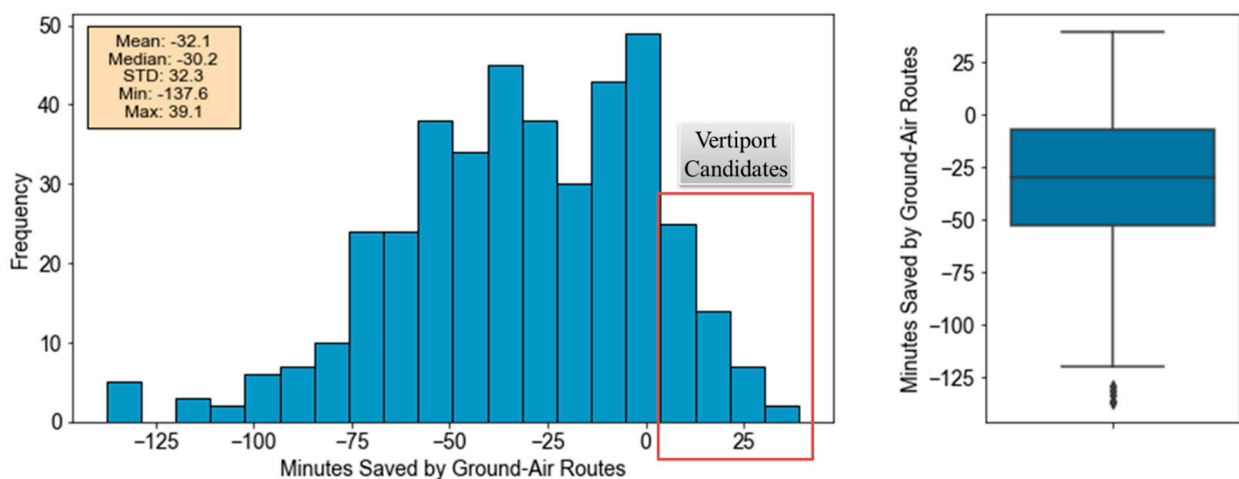

Figure 4. Distribution of time saved by ground–air routes.

Figure 5 compares the duration distribution of the drive-only and ground–air trip subsets from the optimized mixed-mode routes. Figures 5a and 5c plot the histogram of trip duration in minutes for drive-only and ground-air trips, respectively. Figures 5b and 5d are boxplots of trip duration in minutes for drive-only and ground-air trips, respectively. It is clear from these charts that the ground–air subset of the shortest trips tended to take an average of 17.3 min (45.9–28.6) more than the drive-only subset. This was intuitive because the ground–air alternatives would tend to have a greater impact on time savings

for longer-distance ground trips. These findings emphasized the critical role of distance in determining the effectiveness of ground–air transportation options.
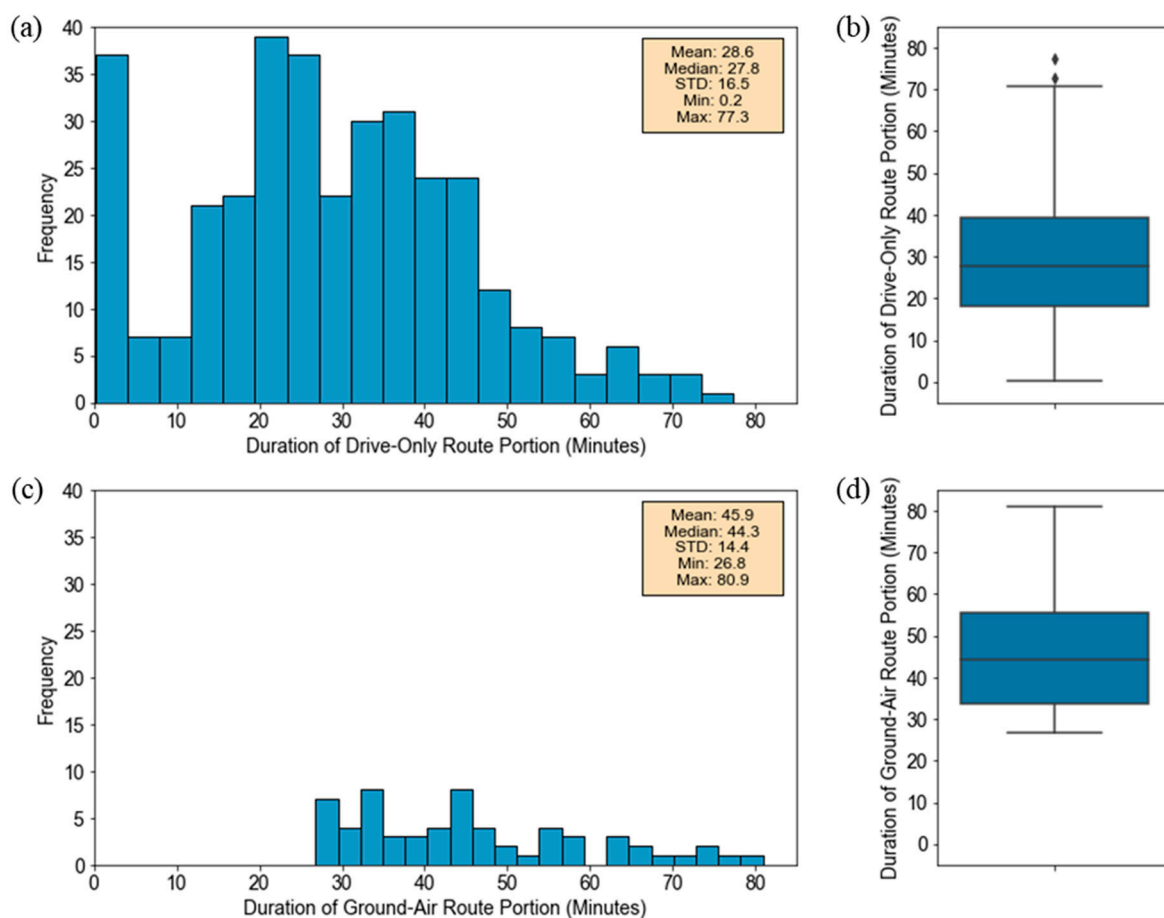

Figure 5. Distribution of drive-only and ground–air route subsets from the optimized mixed-mode trips.

Figure 6 more clearly shows this relationship as a scatter plot of drive time savings against the drive distance to a hospital for every populated ND location. The pattern suggested that positive time savings were more correlated with longer drive distances, even though there were exceptions as visualized. This figure illustrates how longer ground travel distances were associated with greater potential time savings from integrating air travel, providing a clear rationale for the strategic placement of vertiports.

Figure 7 compares the duration distribution of the ground trip ends for the ground–air trips. Figures 7a and 7c plot the histogram of drive time in minutes to non-hospital airports and from hospital airports, respectively. Figures 7b and 7d are boxplots of drive time in minutes to non-hospital airports and from hospital airports, respectively.

The results indicated that the average drive time from a place to a nearby airport was less than 10 min, and the average drive time from an arrival airport to its closest hospital was less than 5 min. These short ground segments emphasized the efficiency of using AAM for medical transport, significantly reducing the time that patients spent traveling by road. These findings highlight the efficiency of AAM in reducing overall transport times, especially in rural settings where ground travel can be lengthy. Figure 8 indicates that the average flight time was 22 min with a maximum duration of less than 40 min, which was well within the capability of eVTOLs suitable for this application [33]. These results highlight the feasibility of integrating eVTOLs into EMS, providing rapid and reliable transport options that can complement ground transportation, especially over longer distances.
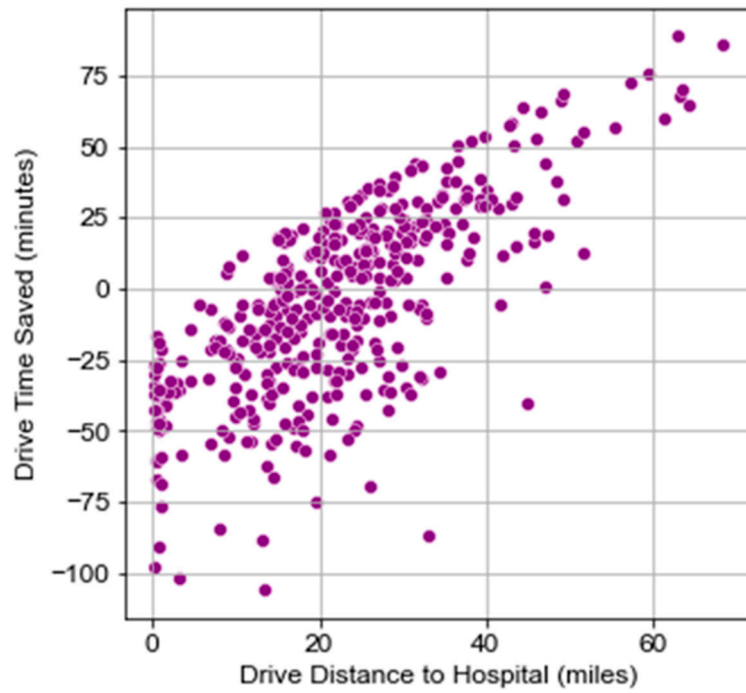
Figure 6. Relationship between drive time savings and drive distance to hospitals for each ND location.
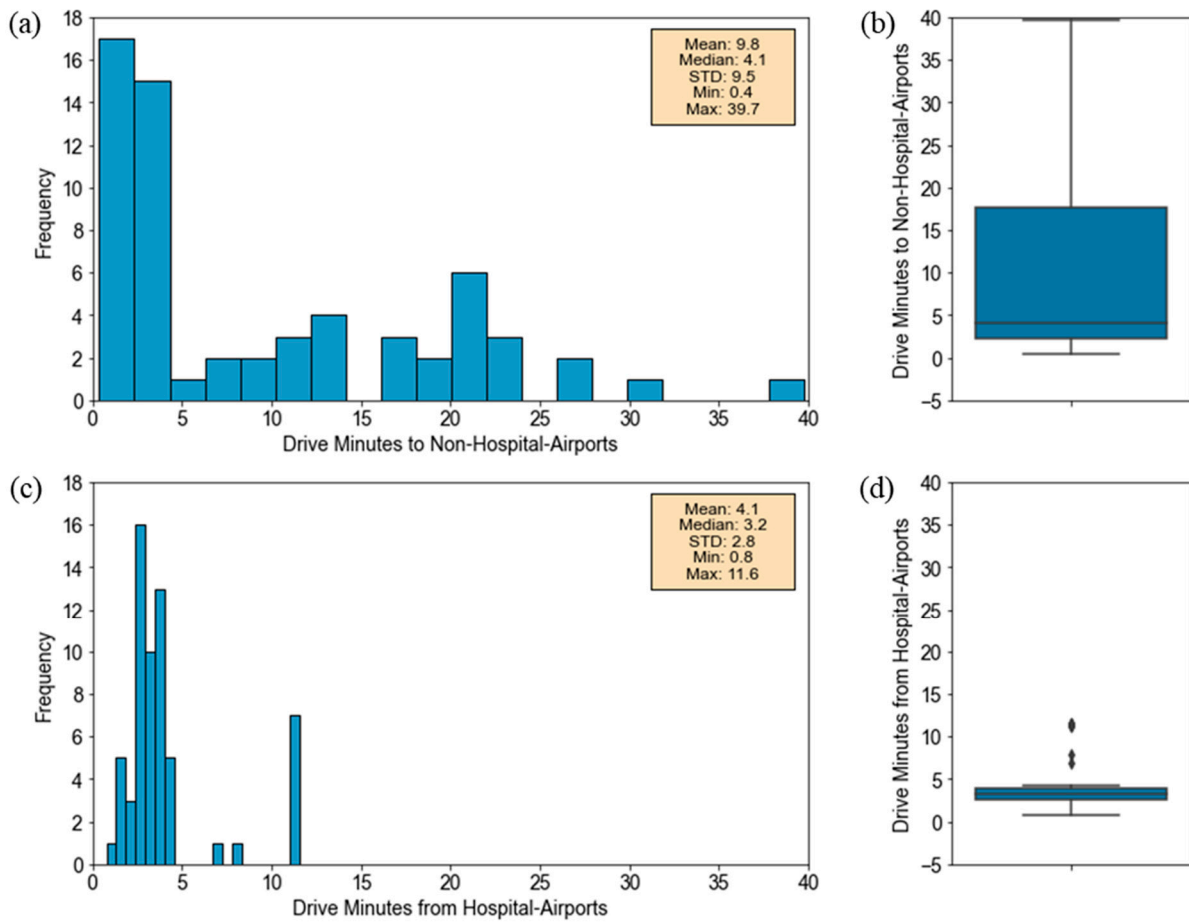

Figure 7. Trip time distribution of the ground portion of ground–air trips.
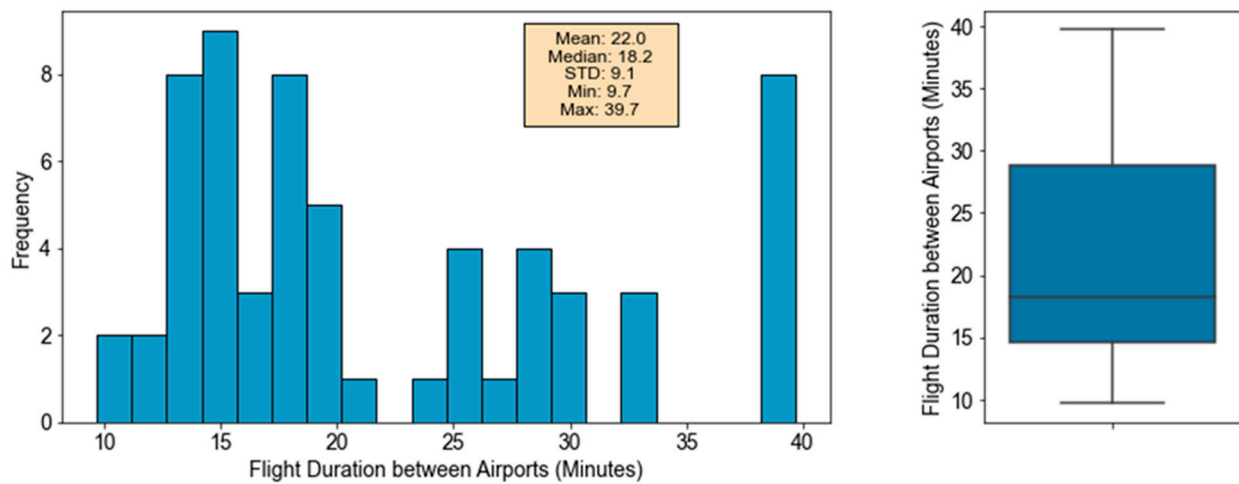
Figure 8. Trip time distribution of the flight portion of ground–air trips.

4.3. Vertiport Site Selection

Table 2 lists the hospitals assigned to places with positive drive time savings. The table includes the hospital type as either a critical access hospital (CAH) or general acute care (GAC) and the operating mode (OM) as either non-profit (NP), government (GV), or proprietary (PR). Other information includes the number of beds, the heliport (HP) designation if present, the total drive minutes saved (DMS), and the total population (POP) for all the places assigned to that hospital. PHR is the product of the population and the drive time savings in hours to indicate a person-hour metric for ranking the potential impact on time savings. The results suggested that Tioga Medical Center (TMC) and Essentia Health Fargo (EHF) were the top hospitals to consider for enabling an air transport option for the longest-distance places assigned to them.

Table 2. Hospitals selected.

Hospitals	Type	OM	Beds	HP	DMS	POP	PHR
Tioga Medical Center (TMC)	CAH	NP	18		43.0	5585	1499.5
Essentia Health Fargo (EHF)	GAC	PR	549	ND45	27.4	8350	1495.0
St Aloisius Medical Center (SAM)	CAH	NP	95	ND27	35.9	3373	994.5
West River Regional Medical Center (WRR)	CAH	NP	25		155.4	1711	740.0
CHI Lisbon Health (CLH)	CAH	NP	25		61.5	2237	570.1
CHI Oakes Hospital (COH)	CAH	NP	20		45.6	2630	507.7
CHI St Alexius Health Dickinson (CAD)	GAC	NP	189		49.9	2065	497.6
CHI St. Alexius Health Garrison Hospital (CAG)	CAH	NP	22		26.0	949	411.6
Sakakawea Medical Center	CAH	NP	18	ND50	20.9	1526	256.0
St Andrews Health Center	CAH	NP	25		46.0	875	233.7
Wishek Community Hospital	CAH	NP	24		29.6	1191	222.9
Kenmare Community Hospital	CAH	GV	19		25.6	897	179.0
Sanford Medical Center Mayville	CAH	NP	18		28.8	1237	175.0
Pembina County Memorial Hospital	CAH	NP	19		15.8	1405	159.1
Nelson County Health System	CAH	NP	25		11.1	683	126.0
CHI St Alexius Health Turtle Lake	CAH	NP	19		12.1	1635	99.7
Trinity Health Hospital	GAC	NP	251	2ND4	26.2	211	92.0
Altru Hospital	GAC	NP	277		3.7	1260	76.7
Towner County Medical Center	CAH	NP	19	ND28	12.1	481	56.6
Sanford Medical Center Hillsboro	CAH	NP	19		10.0	328	54.8
St Luke's Hospital	CAH	NP	20		22.4	405	50.6
Jamestown Regional Medical Center	GAC	NP	134		9.6	281	45.0
Unity Medical Center	CAH	NP	14		0.5	229	0.9
Total					719.1	39,544	8544.1

Figure 9 plots the person-hours saved by enabling an air transport option for each hospital. The ranked trend shows a distinct point of diminishing returns on person-hours saved after the top eight hospitals. In particular, establishing an air transport option to access these eight hospitals would save 6715.9 person-hours over drive-only alternative routes. Table 3 lists the top eight hospitals and the airports assigned to enable the shortest ground–air routes. For example, enabling an air transport option for the towns of Stanley, New Town (NHA2), and Four Bears Village requires establishing vertiports at Stanley Municipal (NHA1), New Town Municipal Airport, and Tioga Municipal airports (HA). The table also includes the towns covered with their populations. Figure 9 annotates the number of vertiport locations required for each hospital, e.g., three vertiports (3V) to establish an air route for Tioga Medical Center. Figure 2 presented earlier highlights these selected hospitals and airports as indicated with the boxed labels and arrows.
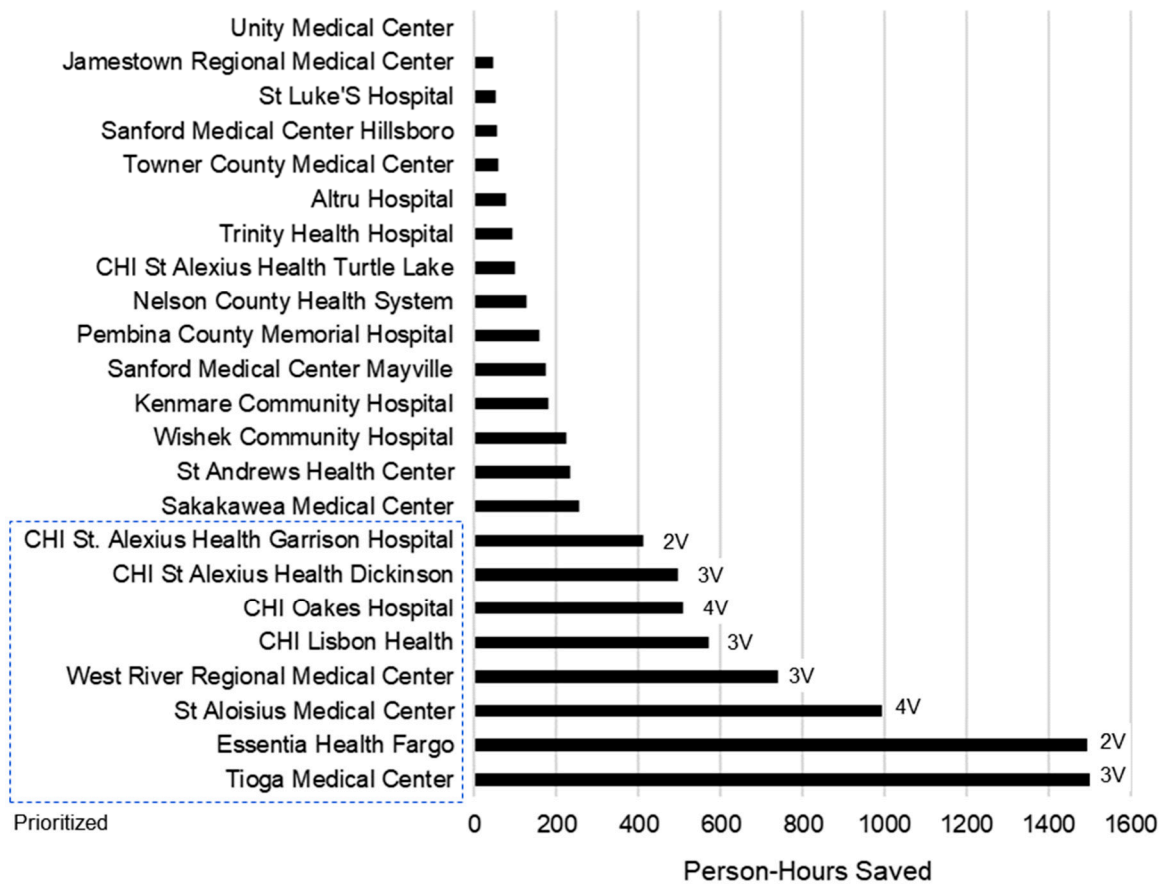

Figure 9. Hospitals ranked by person-hours saved over drive-only route alternatives.

Table 3. Airports assigned to shortest ground–air routes to hospitals and populations covered.

Hospital	NHA1	NHA2	NHA3	HA	Towns (Population)
TMC	Stanley Muni	New Town (NT) Muni		Tioga Muni	Stanley (2321), New Town (2764), Four Bears Village (500)
EHF	Harry Stern (HS)			Hector Intl	Fairmount (343), Wahpeton (8007)
SAM	Fessenden-Streibel Muni (FSM)	Maddock Muni	Rugby Muni	Harvey Muni	Fessenden (462), Maddock (402), Rugby (2509)

Table 3. *Cont.*

Hospital	NHA1	NHA2	NHA3	HA	Towns (Population)
WRR	Elgin Muni	Mott Muni		Hettinger Muni	Elgin (543), Heil (15), New Leipzig (218), Leith (28), Mott (652), Carson (254)
CLH	Lidgerwood Muni (LM)	Milnor Muni		Lisbon Muni	Lidgerwood (600), Hankinson (921), Mantador (67), De Lamere (25), Milnor (624)
COH	Edgeley Muni	Ellendale Muni	La Moure Rott (LMR) Muni	Oaks Muni	Edgeley (585), Ellendale (1125), Berlin (31), LaMoure (764), Marion (125)
CAD	Beach	Dunn County Weydahl (DCW)		Theodore Roosevelt Rgnl (TRR)	Beach (981), Golva (84), Sentinel Butte (61), Killdeer (939)
CAG	Parshall-Hankins (PH)			Garrison Muni	Parshall (949)

4.4. Impact of Hospital Heliports

Placing vertiports at the five hospitals that have heliports as indicated in the table will eliminate the final air-to-ground transfer time. In addition, landing at the hospital facilities will eliminate the ground transport time. Some cases will either minimally increase or decrease the flight time, depending on the hospital location relative to the airport along the flight path. As a case example, Harry Stern Airport serves the towns of Wahpeton and Fairmount. Flying north from Harry Stern Airport to Hector International Airport, about 42 nautical miles, will take approximately 25 min. Flying directly to Essentia Health Hospital instead, about 37 nautical miles, will take approximately 22 min, which is 3 min faster. Hence, the total time savings would be 3 min of flight time, 5 min of transfer time, and 11.6 min of ground travel time, for a total of just under 20 min. In another case example involving St. Aloisius Medical Center, flying northwest from FSM to Harvey Municipal Airport is 13.8 nautical miles (8.3 min), whereas flying directly to the hospital instead is 12.7 nautical miles (7.6 min) for a savings of only 0.7 min. The drive from Harvey Muni to the hospital is 2.8 min. Hence, the total time saved by flying directly to St. Aloisius Medical Center would be 0.7 (flight time) + 5 (transfer time) + 2.8 (drive time) = 8.5 min.

4.5. Ground Travel Savings

Figure 10 shows the distribution of ground travel time saved by taking ground–air routes. This represents the difference between drive-only and the total ground-travel time at the two end trips that involve intermediate air travel. The proportion of drive-only routes that required less ground travel by utilizing air connections was 45.3%. These savings can become significant when ground travel becomes difficult or unreliable due to weather conditions, traffic situations involving congestion or bottlenecks due to oversized or slow-moving vehicles, or road construction. During inclement weather, agencies can prioritize clearing snow on roads that provide a short connection to either the vertiports or to hospitals. Figure 11 shows the top 30 ND towns that will benefit most by utilizing vertiports to save ground travel time. Intermediate air travel also saved travel time for all of these towns, ranging from 12.4 min for Westhope to 39.1 min for Elgin.
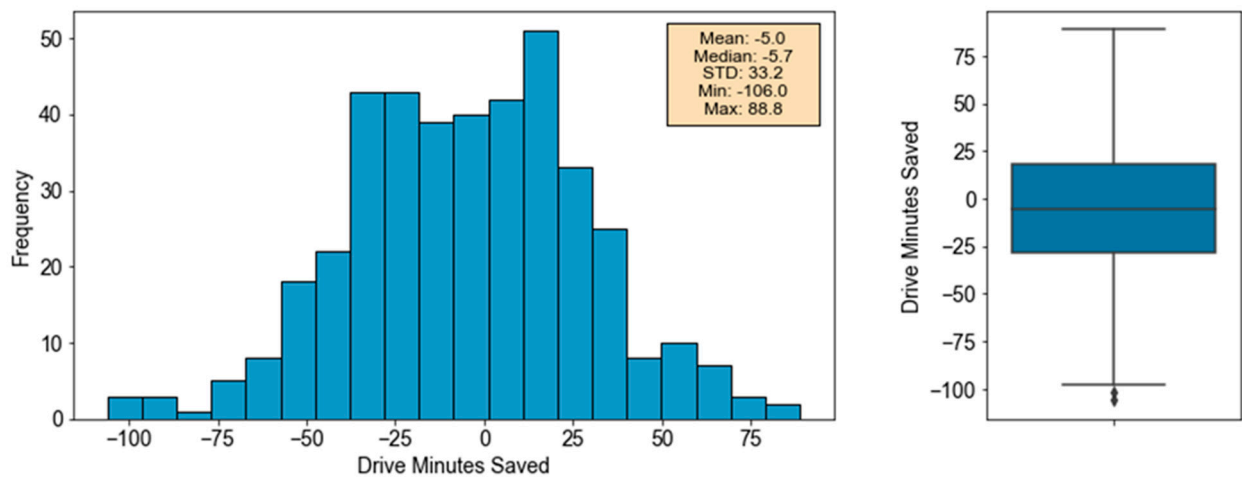
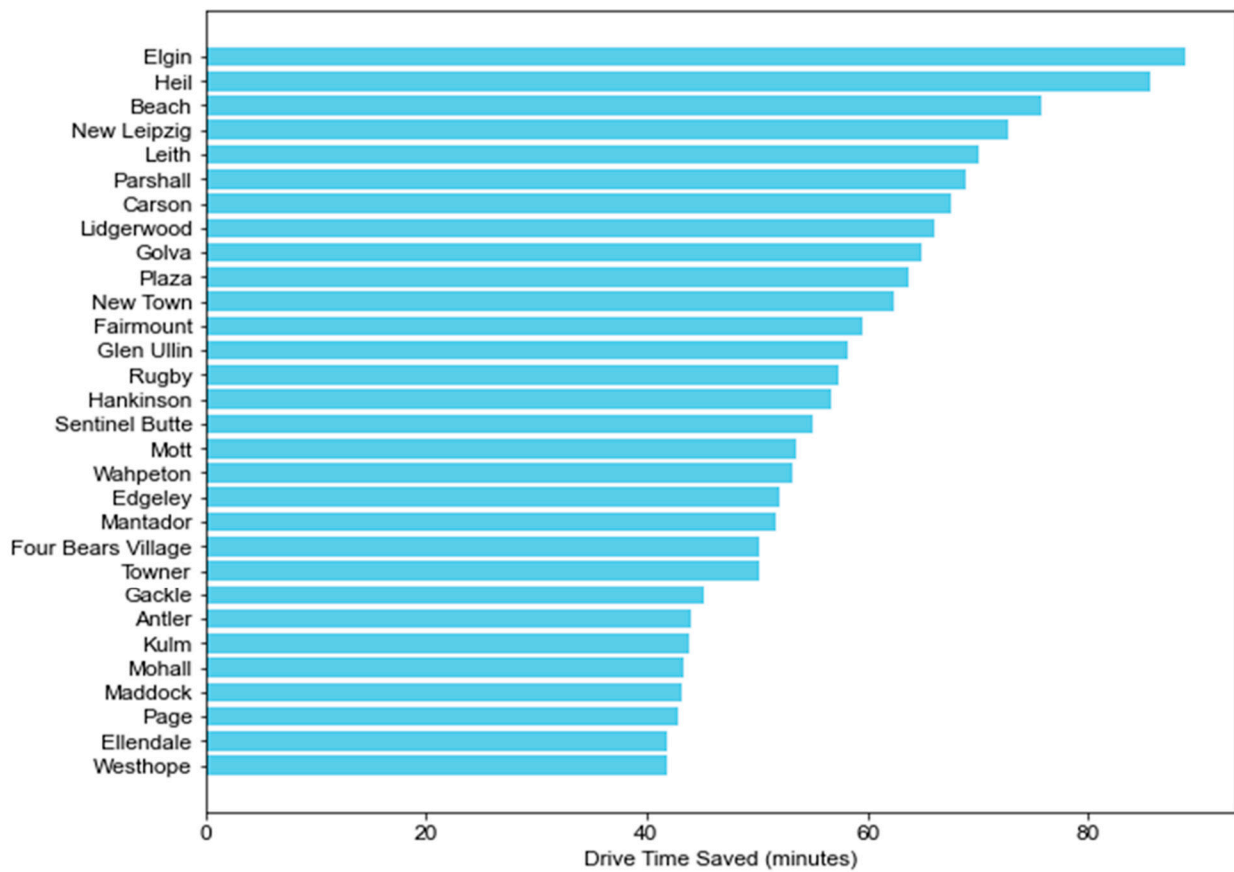**Figure 10.** Distribution of ground travel time saved by ground–air modes.

Figure 11. Top 30 towns that will benefit most by using vertiports for ground travel time savings.

5. Discussions

This study's findings suggested that strategic placement of vertiports could significantly reduce patient transport times, particularly in rural areas. The results indicated that while average time savings may appear modest, the maximum potential savings were substantial, offering a critical advantage in emergency situations. The optimized mixed-mode routes, which integrated both ground and air travel, demonstrated a capacity to reduce extreme travel times by up to 21.8 min compared with drive-only routes. This reduction, although affecting a limited number of locations, highlights the importance of AAM in addressing specific high-need cases. The scatter plot of drive time savings against

drive distance (Figure 6) further corroborated the correlation between longer ground travel distances and greater time savings with AAM integration.

In additional findings, the distribution of ground trip times for ground–air trips (Figure 7) indicated that the average drive time from a place to a nearby airport was less than 10 min, while the average drive time from the arrival airport to its closest hospital was less than 5 min. These short ground segments emphasized the efficiency of using AAM for medical transport, significantly reducing the time that patients spent traveling by road. This reduction in ground travel time was particularly beneficial in rural areas where hospitals may be far from patient locations. Shorter ground travel times contributed to an overall quicker medical response, enhancing patient outcomes by reducing the time to critical care. Figure 9 ranks hospitals by the person-hours saved through the implementation of ground–air transportation routes. The ranked trend showed a clear point of diminishing returns, where the top eight hospitals accounted for a substantial portion of the total person-hours saved. This ranking highlights the importance of strategically selecting vertiport locations to maximize the impact of AAM on EMS. Figure 10 presents the distribution of ground travel time saved by utilizing ground–air modes compared with drive-only trips. The results showed that using ground–air routes reduced the ground travel time over drive-only routes for more than 45% of the locations. These savings become increasingly important in scenarios involving inclement weather, traffic congestion, or other road-related issues that can delay ground transportation.

The optimal placement of vertiports in rural areas presents significant implications for EMS and broader healthcare logistics. First, reducing patient transport times can improve survival rates and health outcomes, especially in cases of acute medical emergencies such as cardiac arrest or severe trauma. For instance, studies have shown that survival rates for out-of-hospital cardiac arrest victims increase significantly with quicker access to medical care. Second, the integration of vertiports into existing medical infrastructure could enhance the flexibility and responsiveness of emergency services. By enabling rapid patient transport, medical personnel, and critical supplies, AAM can ensure timely medical intervention in remote and underserved areas. This aligns with the broader objectives of enhancing healthcare accessibility and equity. Moreover, the strategic placement of vertiports at existing airports and hospital heliports minimizes community disruption and leverages underutilized infrastructure. This approach not only optimizes resource use but also facilitates smoother integration into current transportation networks, thereby reducing implementation barriers.

In addition to its applicability in rural settings, the GIS-based optimization workflow developed in this study can be adapted for use in urban areas with high traffic congestion. During peak travel times, strategic placement of vertiports can provide a viable alternative to ground transportation, thereby reducing delays and improving response times for emergency medical services.

This research advances the body of knowledge in several key areas. First, it provides empirical evidence supporting the feasibility and benefits of AAM in rural healthcare logistics. The GIS-based optimization workflow developed in this study offers a replicable model for other regions seeking to implement AAM solutions. By demonstrating substantial time savings and identifying optimal vertiport locations, this study lays the groundwork for future AAM deployments. Second, this research contributes to the literature on optimization by extending traditional models to include mixed-mode transportation solutions. The integration of ground and air travel in the optimization framework addresses the unique challenges posed by AAM and offers a novel approach to minimizing patient transport times. Finally, the case study provides valuable insights for policymakers and stakeholders, particularly in prioritizing life-saving applications in rural areas where initial deployments can pose fewer risks in terms of the safe integration of AAM aircraft into the national airspace. The findings of this study show that optimized mixed-mode routes can reduce patient transport times compared to drive-only routes, highlighting the critical advantage of integrating ground and air travel.

Another critical factor to consider is the impact of air traffic on the timing and efficiency of air routes. In urban environments, increased air traffic could lead to potential delays in air transportation. Thus, effective air traffic management and coordination with existing air traffic control systems are essential to ensure that urban communities can fully realize the benefits of AAM. Policymakers and stakeholders should prioritize the development of regulatory frameworks that facilitate seamless integration of eVTOL aircraft into the existing airspace and transportation infrastructure.

In comparison to traditional optimization models such as the TSP and the VRP, the GIS-based optimization workflow of this study offers several advantages. It incorporated mixed-mode transportation solutions, integrating both ground and air travel to minimize patient transport times. While TSP and VRP models focus on minimizing travel distances or costs, the approach of this study emphasized time savings, which is crucial for emergency medical services. Furthermore, this work brings several novel contributions to the field of AAM and EMS. It provided empirical evidence supporting the feasibility and benefits of integrating ground and air transportation, developed a replicable GIS-based optimization workflow, and identified optimal vertiport locations to maximize time savings. By demonstrating substantial time savings and addressing practical implementation challenges, this study lays the groundwork for future AAM deployments, offering valuable insights for policymakers and stakeholders.

Despite its contributions, this study has several limitations. First, the analysis was based on data specific to North Dakota, which may limit the generalizability of the findings. Factors such as geographic characteristics, population density, and existing infrastructure can vary significantly across regions, potentially affecting the applicability of the results. Second, the study assumed average travel speeds and nominal transfer times, which may not accurately reflect real-world conditions at all times. Variations in traffic, weather, and operational efficiency could impact the actual time savings achieved. To address the limitations related to traffic, weather, and potential conflicts with civil aviation, planners can employ several mitigation strategies. Incorporating real-time traffic and weather data can enhance the accuracy of travel time estimates and route optimization. Additionally, close coordination with civil aviation authorities can help manage airspace conflicts and ensure safe integration of eVTOL aircraft. Hence, analysts can apply the same methodology to various regions by adopting these strategies that consider local factors for practical implementation. Future research should consider incorporating more dynamic and real-time data to refine these estimates. AAM aircraft currently require vertiports or vertipads for takeoff and landing. Future implementation could potentially use open fields and roads to complete EMS trips, potentially eliminating the need for intermediate airports.

Furthermore, the study did not account for potential regulatory and operational challenges associated with AAM deployments. Issues such as airspace management, safety regulations, and public acceptance are critical factors that stakeholders must address to ensure successful implementation. Comprehensive stakeholder engagement and regulatory frameworks are essential to mitigate these challenges. Finally, the study primarily focused on time savings as the primary benefit of AAM in EMS. While this is a critical factor, stakeholders can explore other potential benefits such as cost savings, environmental impact, and overall system resilience. A holistic assessment encompassing multiple dimensions of AAM benefits would provide a more comprehensive understanding of its value.

6. Conclusions

This study demonstrated the significant potential of advanced air mobility (AAM) to enhance emergency medical services (EMS) in rural areas by strategically deploying vertiports. In focusing on North Dakota as a case study, the research quantified how the integration of ground and air transportation could reduce patient transport times, particularly for remote and underserved communities. The GIS-based optimization workflow developed in this study not only identified optimal vertiport locations but also provided a replicable model for other regions seeking to implement AAM solutions. While this study

focused on North Dakota, the methodology presented is adaptable to other regions by extracting the data from the national dataset presented and combining locally available data to validate and refine the optimization models. By addressing region-specific challenges and incorporating dynamic data sources, planners can generalize the methodology to enhance emergency medical services in diverse settings.

The results indicate that while average time savings may be modest, the maximum time savings can be substantial, offering life-saving advantages in emergency medical situations. The reduction in ground travel time for more than 45% of the populated locations becomes increasingly important in scenarios involving inclement weather, traffic congestion, or other road-related issues that can delay ground transportation. These results highlight the value of AAM in improving health outcomes and survival rates by ensuring timely medical interventions. Moreover, the strategic placement of vertiports at existing airports and hospital heliports minimizes community disruption and leverages underutilized infrastructure, facilitating smoother integration into current transportation networks. This research advances the body of knowledge by extending traditional optimization models to include mixed-mode transportation solutions, addressing the unique challenges posed by AAM. The study provides valuable insights for policymakers and stakeholders involved in AAM initiatives.

Future research should focus on several key areas to build on the findings of this study. Expanding the analysis to include different geographic regions with varying characteristics would enhance the generalizability of the results. Incorporating more dynamic and real-time data, such as traffic conditions, weather patterns, and operational efficiencies, would refine the time savings estimates and provide a more accurate assessment of AAM benefits under different situations. Additionally, future studies should address the regulatory and operational challenges associated with AAM deployment, including airspace management, safety regulations, and public acceptance. Exploring the potential markets for moving other types of commodities, such as pharmaceuticals and perishable items, could further extend AAM applications in healthcare logistics.

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Abbreviations

The following is a list of abbreviations used in this study:

AAM	Advanced air mobility
BTS	Bureau of Transportation Statistics
BVLOS	Beyond visual line of sight
CAH	Critical access hospital
DMS	Drive minutes saved
EMS	Emergency medical services
eVTOL	Electric vertical takeoff and landing
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
GAC	General acute care
GIS	Geographic information system
GV	Government
HA	Hospital airport
HP	Heliport
HPMS	Highway performance monitoring system

HIFLD	Homeland Infrastructure Foundation-Level Data
NDMA	North Dakota Medical Association
NHA	Non-hospital airport
NP	Non-profit
NTAD	National Transportation Atlas Database
OD	Origin–destination
PHR	Person-hour ratio
PR	Proprietary
QNEAT3	QGIS Network Analysis Toolbox
STD	Standard deviation
TSP	Traveling salesman problem
UAV	Uncrewed aerial vehicles
USDOT	United States Department of Transportation
VRP	Vehicle routing problem

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