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REGIONAL AIR MOBILITY MARKET STUDY

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Abstract

Recent years have witnessed a renewed interest in regional air mobility operations. After several decades of decline, the convergence of new technologies and the improvements in efficiency brought by electrified powertrains and autonomy have brought optimism within regional air mobility operators. In this research, we investigate whether technologies and revamped concepts of operations are sufficient to re-energize this market segment. To do so, we first describe a new concept of operations using underutilized regional airports to offer regional air services aboard state-of-the-art small size regional aircraft. We then quantify the demand for regional air mobility services using the four-step demand model. Using a scheduling and fleet assignment optimization developed in-house, we then assess the demand for new efficient regional aircraft. The method is applied to the entire United States on a region-by-region basis. This allows the comparison and contrasting of the results and helps identify the conditions for successful regional air mobility operations.

Keywords: Regional Aviation, Thin Haul, Market Analysis, Passenger Demand

1. Introduction

1.1 Regional Aviation in the United States

Prior to the 1978 Airline Deregulation Act, the networks of many airlines in the United States featured point-to-point routes. Many of these routes were operated by commuter operators flying a wide variety of small piston and turboprop regional aircraft, often seating between 9 and 50 passengers. After the 1978 deregulation, the network structure of many airlines evolved with the introduction of hubs. Cook and Goodwin [1] argue that the air transportation system in the United States is now mostly articulated around the hub and spoke model which aggregates demand into large hubs using regional aircraft, then fly passengers to other hubs using large capacity aircraft, before finally dispatching passengers to their destination aboard regional aircraft. While there are several benefits to this network topology, including the ability to serve smaller communities thanks to the aggregation of passenger demand, one drawback is the need to connect at hubs which significantly stretches itineraries and makes shorter routes unattractive. In addition, following the consolidation in the United States airlines industry, fewer and fewer hubs exist today, and the remaining ones are often massive and congested, thus stretching transit times.

The liberalization of air travel that followed brought more competition, forcing airlines to be more competitive and focus their attention on controlling costs to maintain profitability [2]. Airlines progressively gravitated towards higher passenger volume markets where larger aircraft can be used, bringing with them economies of scale. It is also widely documented that passengers prefer larger regional jets over smaller turboprop aircraft, with the latter typically perceived as noisy and less comfortable [3, 4]. As a result, many airlines have transitioned their fleet away from smaller commuters and turboprops. This has led aircraft manufacturers to move their development efforts to larger aircraft, and few new offerings for aircraft seating fewer than fifty passengers have been proposed during the past three decades. The fleet of commuters and smaller turboprop aircraft is therefore ageing which brings additional challenges in terms of obsolescence, deteriorating reliability, and increasing operating costs. High operating costs have also been pointed out as one reason air services aboard small-size regional aircraft are not economically sustainable [6]. With an ageing fleet and with recurring and fixed operating costs amortized over a smaller number of passenger-seat miles, operating expenditures expressed in cost per available seat mile tend to be high. This results in high airfares which deter many passengers from using these air services and turn them away to competing modes of transportation.

All in all, this has been the catalyst for many airlines to abandon the use of smaller capacity turboprops and up-gauge flights to larger regional jets. Services to markets that could not support these larger aircraft were subsequently cancelled, thus disconnecting many smaller communities from the rest of the National Airspace System and hindering the economic development and productivity of many places in the country [7].

1.2 Opportunities for significant efficiency improvements

In recent years, a paradigm shift has permeated many government research agencies, aircraft manufacturers, and venture capitalists. The convergence of new technologies in terms of autonomy, electrified powertrains, electric energy storage, and improved materials offers compelling arguments for the design of new, ultra-efficient, and environmentally-friendly small-gauge and short-range regional aircraft. This has led to a Cambrian explosion of new small aircraft designs generated by small startups and established aircraft manufacturers alike. Revamped service aboard these new state-of-the-art small-size regional aircraft has the potential to open many new opportunities as previously unprofitable low-volume routes become economically sustainable again.

1.3 Sustainability considerations

A re-energized commuter aviation will bring additional air traffic to previously quiet airports. With commuter operators already facing local resistance at several small airports across the United States, any increase in aircraft movements will likely exacerbate conflicts with neighboring communities unless sustainability is tackled up front [8]. More generally, as environmental concerns become growing societal issues worldwide and with the airline industry striving to become carbon-neutral by 2050, the potential for an increased carbon footprint from these additional operations must be mitigated early-on during the definition of the concept of operations to get accepted [9]. For these reasons, and because short-haul regional aviation faces competition from other modes of transportation with potentially smaller carbon footprints, the aircraft used in this research have either electric powertrains or hybrid-electric powertrains. This helps mitigate some of the noise-related challenges and minimizes carbon emissions in the atmosphere.

1.4 Objective

The objective of this research is to develop and apply a framework to estimate the demand for advanced regional air mobility services. In the remaining of this paper, the term 'regional air mobility' is used to describe the aggregation of the thin haul market segment (typically using aircraft with a seating capacity of no more than 9 passengers), the commuter operators market segment (using aircraft with fewer than 19 seats), and the small-gauge regional airlines market segment (using aircraft with fewer than 50 seats). We will first try to estimate the demand for these services before trying to quantify the need for new aircraft in the intermediate 19-seat gauge.

2. Regional Travel Demand Estimation

2.1 Regional use-cases

The United States is split into several mega-regions using historical socio-economic reasons (economic centers and their surrounding 'catchment areas'). These regions are usually composed of several states sharing a connected and integrated transportation infrastructure (highways and air transportation services) which makes them good candidates for grouping. In this research, we investigate seven mega-regions: the Northeast Corridor, the Midwest, the Northern Great Plains, the Pacific Northwest, the Southwest, the Southern Great Plains, and the Southeast. The extent of these regions of interest is depicted in the maps provided in Figure 1.

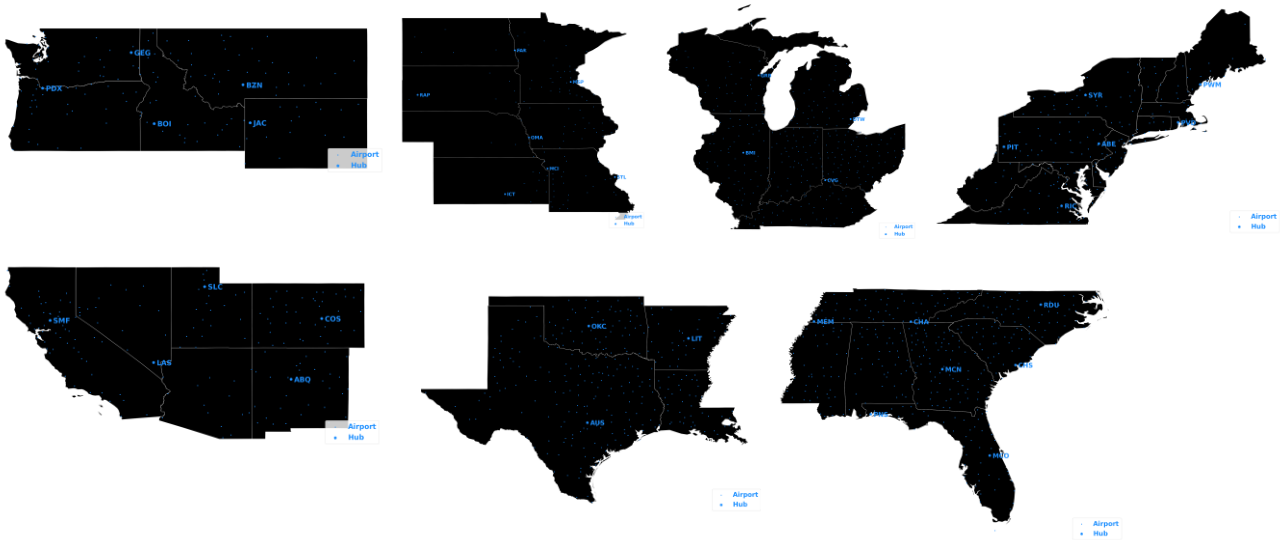


Figure 1: Geographical extent of the seven United States mega regions of interest (counterclockwise from the top right: Northeast Corridor, Midwest, Northern Great Plains, Pacific Northwest, Southwest, Southern Great Plains, Southeast)

2.1.1 Northeast Corridor

This first mega-region encompasses both the New England and Mid-Atlantic areas which include Maine, Connecticut, Rhode Island, Vermont, New Hampshire, and Massachusetts, as well as New York, New Jersey, Pennsylvania, Maryland, Delaware, Virginia, West Virginia, and the District of Columbia. Covering over 237,000 mi^2, the region extends 760 miles North to South and 930 miles East to West. Despite hosting 74 million people or about 22% of the United States' population, fewer than 80 airports in the Northeast Corridor receive scheduled commercial air services as of 2022.

Each county in the U.S. Northeast Corridor is mapped to one public-use airport from the National Plan of Integrated Airport Systems (NPIAS) that will be used to support future regional air mobility services [10]. To ensure these airports are conveniently located, the mapping is done to minimize the distance between the airport and the centroid of population of the county. Finally, to ensure that these airports are adequately equipped to support regional air services, only airports with runways with a length exceeding 2,500 ft and a width exceeding 60 ft are retained. Other considerations could be included as well, such as the availability of runway lighting systems, airport light beacons, and rescue and fire-fighting stations. Nevertheless, the authors believe that these features and services could be added if the airport authority is supportive of these new regional services. The mapping between counties and airports transforms county-to-county markets into airport-to-airport markets.

Among these airports, six are selected as regional hubs where connections between regional air mobility services can happen. These are Portland International Jetport (PWM), ME; Bradley International Airport (BDL), CT; Syracuse Hancock International Airport (SYR), NY; Pittsburgh International Airport (PIT), PA; Atlantic City International Airport (ACY), NJ, and Richmond International Airport (RIC), VA. These airports are selected as connecting hubs for several reasons. First, these are defined as small or medium hubs in the NPIAS which means they have a substantial ground support infrastructure (runways, terminals, gates or parking stands), but typically do not suffer from significant congestion unlike large hubs. Second, their location is close to densely populated areas and there is significant local demand for air transportation. Third, they are geographically well-positioned to capture major regional traffic flows.

2.1.2 Midwest

The second mega-region includes Ohio, Indiana, Illinois, Michigan, Wisconsin, and Kentucky. Covering over 341,000 mi^2, the region extends 750 miles North to South and 570 miles East to West. Despite hosting 54 million people or about 16% of the United States' population, fewer than 50 airports in the Midwest receive scheduled commercial air services as of 2022. Among these airports, four are selected as hub airports for connections between regional air mobility services. These are the Central Illinois Regional Airport at Bloomington-Normal (BMI), the Cincinnati Northern Kentucky International Airport (CVG), the Detroit Metropolitan Wayne County International Airport (DTW), and the Green Bay Straubel International Airport (GRB). Some of these airports are already large hubs or focus cities (DTW and CVG), but airlines have recently scaled back operations at these airports, which means that capacity is still available for new regional services.

2.1.3 Northern Great Plains

The third mega-region includes Minnesota, Iowa, Missouri, North Dakota, South Dakota, Nebraska, and Kansas. Covering over 530,000 mi^2, the region extends 860 miles North to South and 660 miles East to West. Hosting 21 million people or about 6% of the United States' population, the Northern Great Plains region has approximately 60 airports receiving scheduled commercial air services as of 2022. Among these airports, seven are selected as hub airports for regional connections, namely the Minneapolis-St Paul International Airport (MSP), the Hector International Airport Fargo (FAR), the Rapid City Regional Airport (RAP), the Omaha Eppley Airfield (OMA), the Kansas City International Airport (MCI), the St. Louis Lambert International Airport (STL), and the Wichita Mid-Continent Eisenhower National Airport (ICT). Again, some of these facilities are large (MSP, STL), but none of them is at or close to capacity.

2.1.4 Pacific Northwest

The fourth mega-region includes Montana, Idaho, Washington, Oregon and Wyoming. Covering over 498,000 mi^2, the region extends 550 miles North to South and 950 miles East to West. Hosting 15 million people or about 4.5% of the United States' population, the Pacific Northwest region currently has 40 airports receiving scheduled commercial air services. Among these airports, five are selected as hub airports for regional connections, namely the Boise Air Terminal (BOI), the Spokane International Airport (GEG), the Bozeman Yellowstone International Airport (BZN), the Jackson Hole Airport (JAC), and the Portland International Airport (PDX).

2.1.5 Southwest

The fifth mega-region includes Arizona, California, Colorado, New Mexico, Nevada, and Utah. Covering over 700,000 mi^2, the region extends 740 miles North to South and 1,150 miles East to West. Despite hosting 60 million people or about 17.8% of the United States' population, fewer than 60 airports in the Southwest receive scheduled commercial air services as of 2022. Among these airports, seven are selected as hub airports for connections between regional air mobility services, namely the Albuquerque International Sunport (ABQ), the Colorado Spring Airport (COS), the Las Vegas International Airport (LAS), the Ontario International Airport (ONT), the Phoenix Sky Harbor

Airport (PHX), the Salt Lake City International Airport (SLC), and the Sacramento International Airport (SMF).

2.1.6 Southern Great Plains

The sixth mega-region includes Arkansas, Louisiana, Oklahoma, and Texas. Covering over 444,000 mi^2, the region extends 760 miles North to South and 900 miles East to West. Hosting 40 million people or about 12% of the United States' population, the Southern Great Plains region has about 40 airports receiving scheduled commercial air services as of 2022. Among these airports, three are selected as hub airports for connections between regional air mobility services, namely the Austin Bergstrom International Airport (AUS), the Bill and Hillary Clinton National Airport in Little Rock (LIT), and the Will Rogers World Airport in Oklahoma City (OKC).

2.1.7 Southeast

The seventh and final mega region includes Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, and Tennessee. Covering over 444,000 mi^2, the region extends 830 miles North to South and 840 miles East to West. Despite hosting 61 million people or about 18% of the United States' population, fewer than 60 airports in the Southeast receive scheduled commercial air services as of 2022. Among these airports, seven are selected as hub airports for regional connections, namely the Chattanooga Metropolitan Airport (CHA), the Charleston International Airport (CHS), the Memphis International Airport (MEM), the Orlando International Airport (MCO), the Middle Georgia Regional Airport (MCN), the Raleigh-Durham International Airport (RDU), and the Pensacola International Airport (PNS).

2.2 Data products and Technical Approach

To the authors' knowledge, there are no publicly available datasets that forecasts passenger demand for regional air mobility services at the granularity needed to analyze passenger volumes for each origin-and-destination market. On the one hand, research has been carried out regarding the revitalization of regional air mobility but usually does not exhibit sufficient granularity to perform detailed market-by-market analyses [11,12]. On the other hand, forecasts with sufficient granularity to perform detailed market-by-market analyses exist, but do not account for the disruption brought by new regional air mobility services operating from smaller and more convenient regional airports [13]. As a result, the mode split predictions of these forecasts do not reflect the extra convenience offered by these new services.

To mitigate these shortcomings, we propose an updated version of the technical approach described in Justin et al. [14]. This approach relies on a long-distance trip survey performed by the Federal Highway Administration (FHWA) called the Traveler Analysis Framework (TAF) - National Long Distance Passenger Origin Destination [13]. The survey provides estimates of person trip flows for long distance travels, defined as trips greater than 100 miles, between any two counties in the United States. Estimates are provided for a base year of 2008 as well as for a future year of 2040 for different travel modes and purposes, namely air, automobile for business, automobiles for non-business, rail, and bus.

The TAF relies on the four-step travel demand model [15] highlighted in Figure 2. The first step is a trip generation which determines the number of trips originating or ending in each county by trip purpose according to various socio-economic metrics. The second step is the trip distribution which matches origin counties and destinations counties, typically using a gravity-based model. The third step is the mode choice which computes, for each origin and destination county pair, the proportion of trips for each transportation mode. The last step is the route assignment which allocates trips to specific geographical routings. Following the approach of Justin et al. [14, 16], the first two steps are kept untouched, and only the mode choice is revisited to account for the availability of new regional air mobility services operating from more convenient airports. This assumes that the availability of new regional air mobility services does not stimulate the overall demand for transportation, but only changes the fraction of people traveling by air (i.e., for each origin-destination county pair, the total number of travelers remains the same, but the share of passengers choosing air transportation may change).

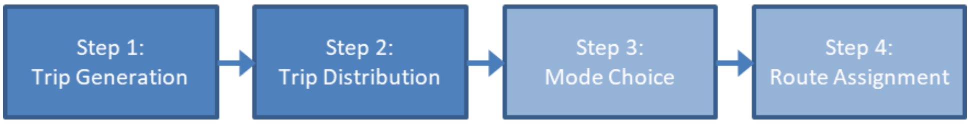


Figure 2: Four-step travel demand model

To predict the number of passengers selecting air transportation for each origin and destination market, the third step is revisited using an empirically calibrated utility function and mode-choice model. Historical travel demand datasets from the TAF for year 2008, historical airfares, historical set of airports receiving commercial air services in 2008, historical air travel times, and historical driving times are used to hypothesize a utility model based on the generalized cost of travel. The utility is used next in a multinomial logit model to estimate the mode choice of travelers in 2008. This estimate is then compared to the observed mode choice of long-distance travelers in year 2008 from the TAF dataset to calibrate the hypothesized utility model using a maximum likelihood estimation.

With the utility and mode choice calibrated, a traveler behavior model is obtained that helps understand how long-distance travelers make their mode choice as a function of travel cost and travel time. This traveler behavior model is applied next to the total passenger demand across all travel modes for each county-to-county market to estimate what fraction of travelers will choose air transportation in 2040 once services from convenient airports are offered. To do so, the demand datasets from the TAF for year 2040 are used in conjunction with updated set of airports, updated air travel times, updated driving times, and airfares. The proposed calibration-application approach to estimate demand for regional air mobility services in 2040 is depicted in Figure 3, and the following subsections detail salient features of this approach.

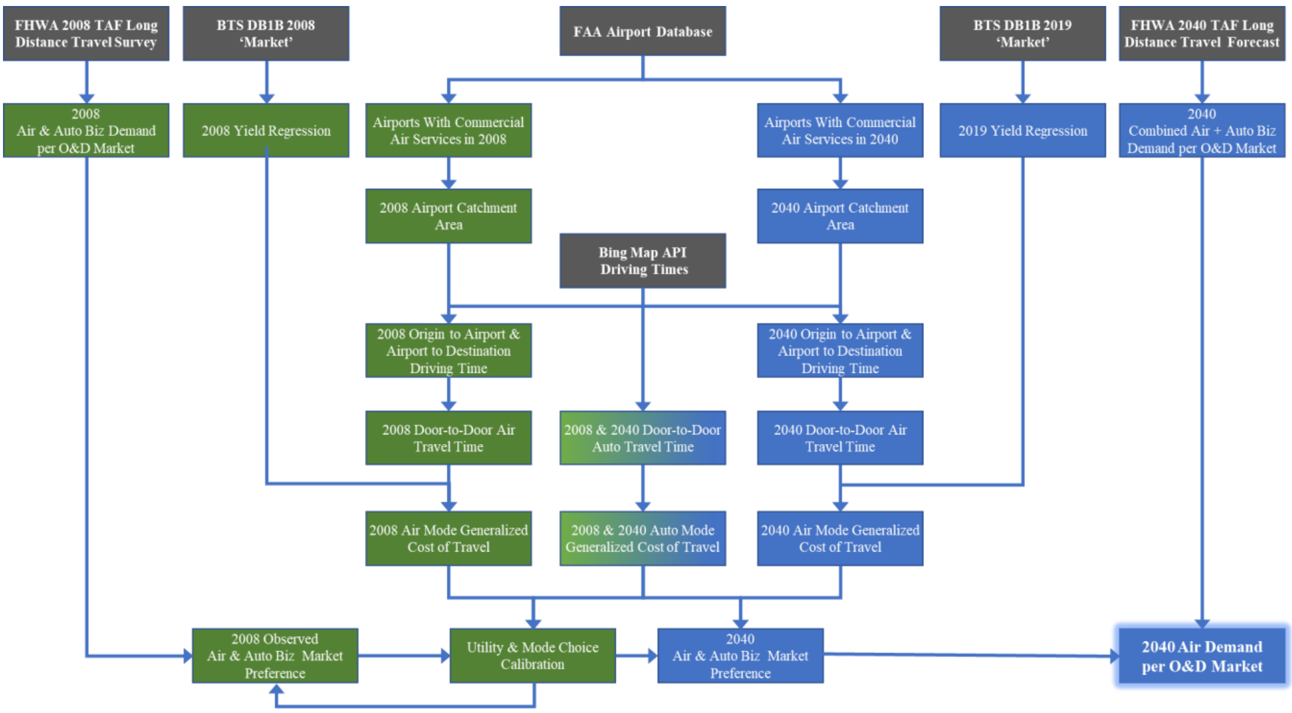


Figure 3: Technical approach

2.3 Traveler modeling

In this research, regional air mobility services are assumed to be air services offered aboard small capacity vehicles seating between 9 and 50 passengers (although we focus on the 19-seat gauge later) and flying over short distances, typically envisioned to be between 50 miles and 350 miles. It is important to note that the overall travel is typically longer than 100 miles, but the actual air travel distance may be shorter depending on departure and arrival airport locations. Owing to the short nature of these flights and owing to the possibility of mode substitution, we assume that users of these services are time-sensitive passengers likely to be traveling for business purposes. Among these, three types of travels are associated with regional air mobility services, and these are highlighted in Figure 4. There are passengers who travel within a region, passengers who travel to a large airport within the region to connect to a longer haul flight, and finally passengers who travel from a large airport within the region after connecting from a longer haul flight.

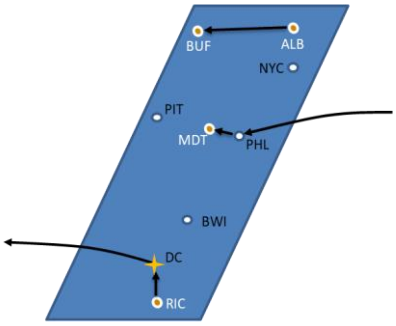


Figure 4: Potential users of advanced regional air mobility services

2.4 Travel time modeling

For regional air mobility services to be successful, they must provide value to the customer in terms of travel time savings. The door-to-door journey of long-distance travelers needs to be estimated using the two modes of transportation most likely to be used by business travelers in the United States, namely auto transportation and air transportation. Because the TAF survey used as foundation for this analysis provides long distance travel demand on a county-to-county basis, there is no information as to where travelers truly originate within the origin county or truly go within the destination county. For this reason, we assume that all travels start and end at the county centroid of population.

For a transportation using exclusively automobiles, the Bing Map API [17] is used to query the door-to-door distances and driving times at both quiet and rush hours. For a transportation using cars and aircraft, the door-to-door travel time is computed by adding the driving time from the origin to the departure airport, the time spent at the origin airport, the time spent in the air, the time spent at the destination airport, and finally the driving time from the arrival airport to the destination. In the case of connecting flight, a connecting time is also added to account for the time spent at the connecting hub in between the two regional air mobility flights. The driving times between county centroids and airports is estimated again using the Bing Map API [17]. As highlighted in Figure 5 and Figure 6, the block time of flights is estimated using either the FlightAware website [18] for flights operated by commuter piston aircraft, commuter turboprop aircraft, and regional jets in 2008, or using datapoints retrieved while running mission analyses for flights of various lengths operated by a notional hybrid-electric 19-seat aircraft .

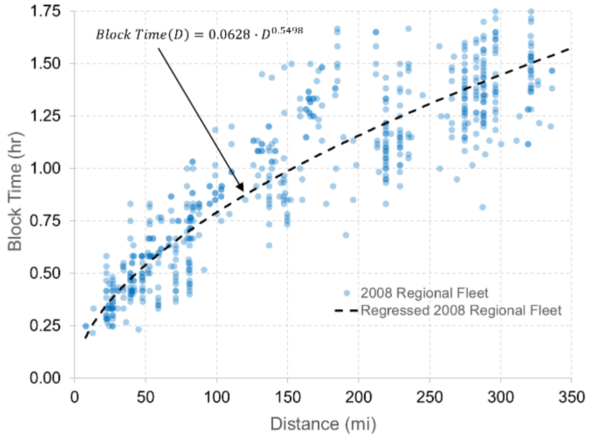


Figure 5: Historical regression of block time for 630 regional flights from 2008

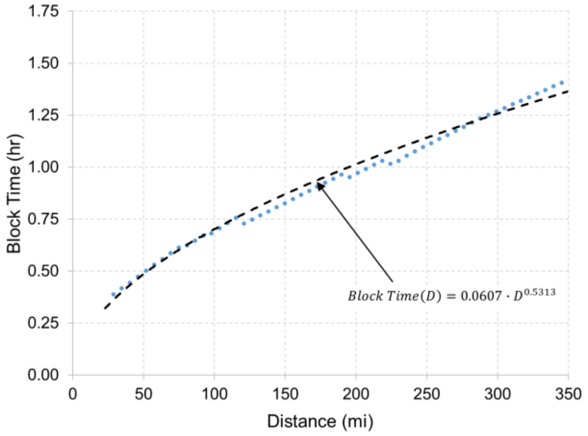


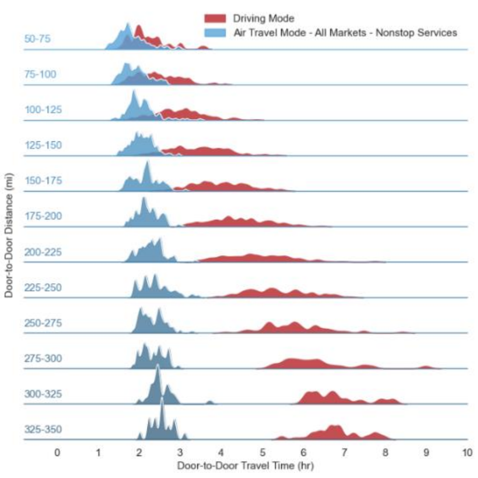
Figure 6: Regression from mission analysis datapoints for a hybridized 19-seat regional air mobility aircraft

The times spent at the departure and destination airports are estimated to be 60 min at the departure airport and 30 min at the destination airport in 2008. For flights in 2040, the time spent is estimated to be 25 min at the departure airport and 10 min at the destination airport reflecting operations from smaller uncongested airports. Finally, if the itinerary is connecting, an additional 60 min is budgeted for the connection in between the two flights.

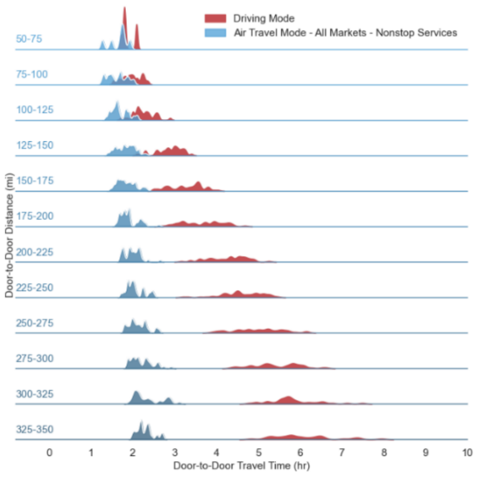
Comparisons of door-to-door transportation times between the ground mode (exclusively automobile) and the air mode (combination of automobile and aircraft) are provided in Table 1 for nonstop regional air mobility services and in Table 2 for connecting regional air mobility services. Both tables contain seven graphs representing the results for each of the seven mega-regions under review. Each graph represents the distributions of ground (red) and air (blue) transportation time, categorized by the great circle distance of the underlying county-to-county markets (titled door-to-door distance). While these distributions overlap for shorter distances, they spread apart as the door-to-door distance increases. For most markets under investigation, the distance threshold for nonstop air services to be *statistically* competitive from a time-saving perspective is approximately 125 miles. This seems to be valid for all seven regions under review, regardless of the population density, airport density, or density of highway and interstate infrastructure. This threshold increases to approximately 250 miles for connecting air services. Consequently, we can expect the demand for connecting regional air mobility services to be substantially lower than the demand for nonstop regional air mobility services.

Table 1: Door-to-door ground transportation times and nonstop air transportation times, categorized by the door-to-door distances of the underlying markets

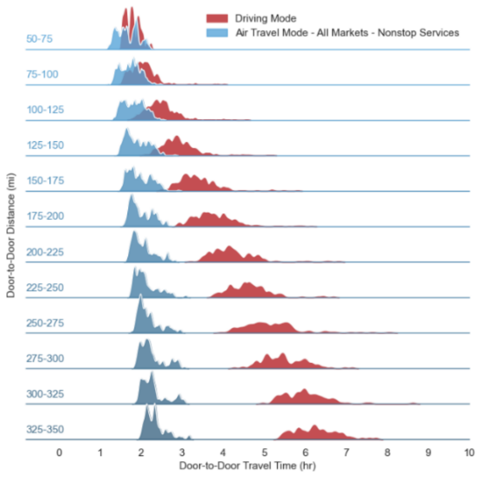
Pacific Northwest



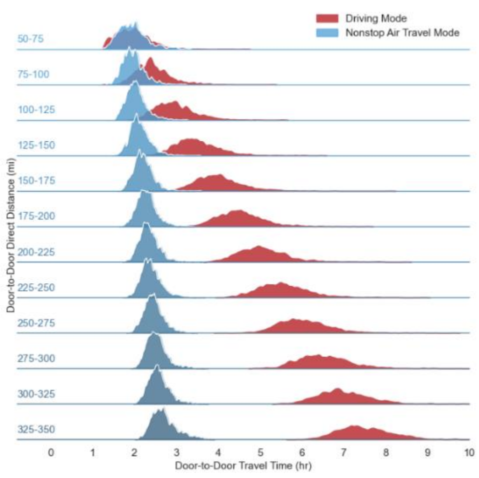
Northern Great Plains



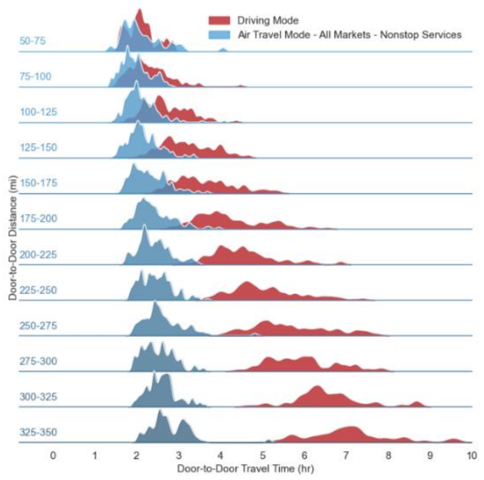
Midwest



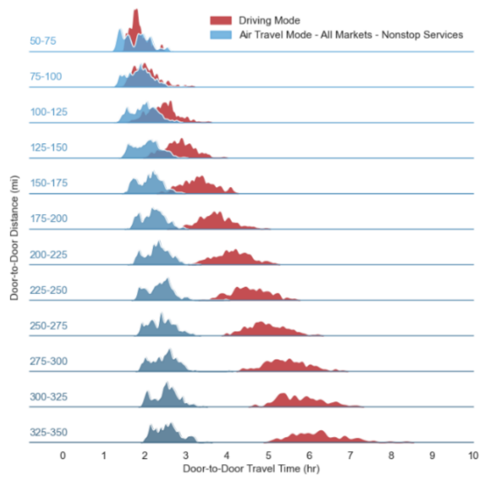
Northeast Corridor



Southwest



Southern Great Plains



Southeast

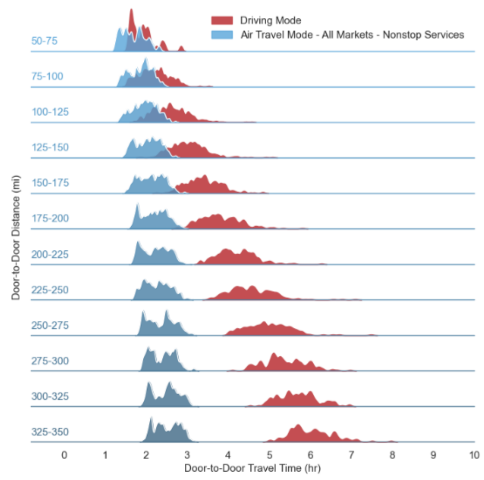
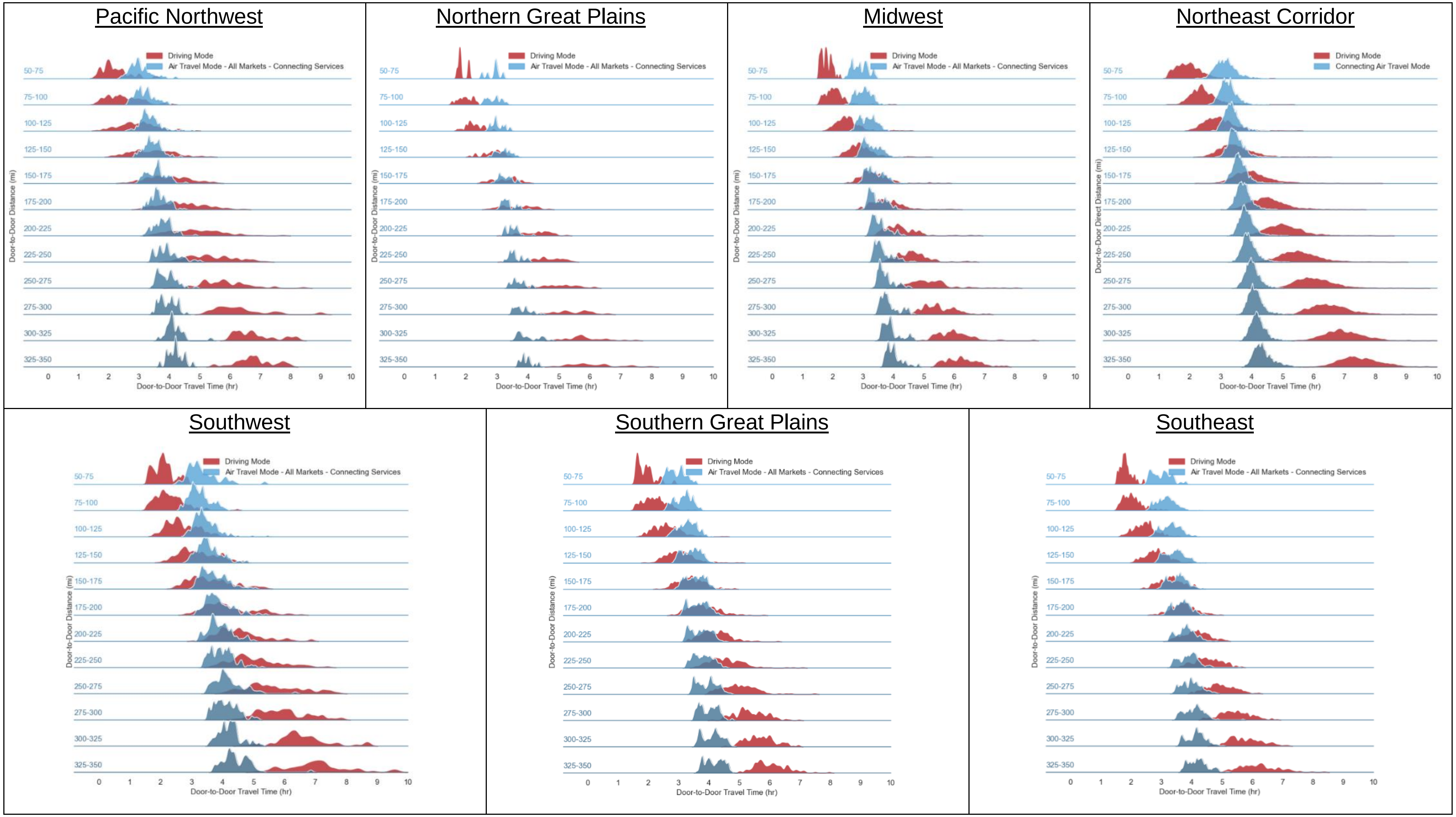


Table 2: Door-to-door ground transportation times and connecting air transportation times, categorized by the door-to-door distances of the underlying markets



2.5 Travel cost modeling

Long distance travelers will switch to regional air mobility services if the time savings can be offered at a reasonable price point. To estimate driving costs, we use the historical and current Internal Revenue Service standard mileage reimbursement rate [19] as well as estimates of the driving distances from Bing Map [18]. To estimate the flying cost, we use regressions from regional and short-haul economy-class airfares of nonstop and one-stop itineraries from the Bureau of Transportation Statistics DB1B database [20]. We use a 2008 dataset to do an historical regression of airfare yields and we use the 2019 dataset for projections into the future as this is the most recent pre-COVID dataset. Figure 7 and Figure 8 highlight regressions of the yield, which is indicative of what passenger pay, and of the base yield, which is indicative of what airlines earn (by removing taxes, fees, and user charges). The cost of the door-to-door ground transportation is simply the driving cost, while the cost of the door-to-door air transportation is the sum of the driving cost to the departure airport, the flying cost, and the driving cost from the arrival airport.

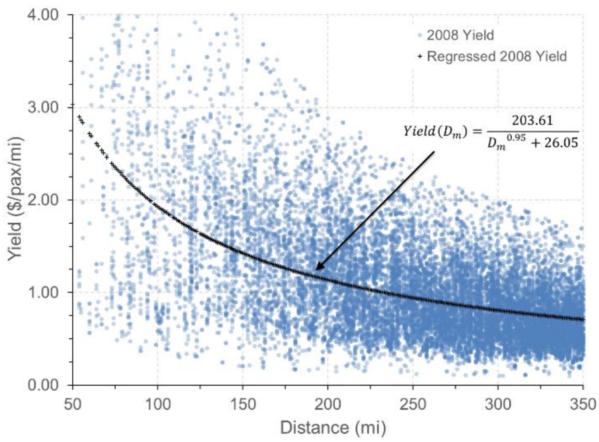


Figure 7: Yield for 38,700 nonstop and one-stop itineraries from 2008

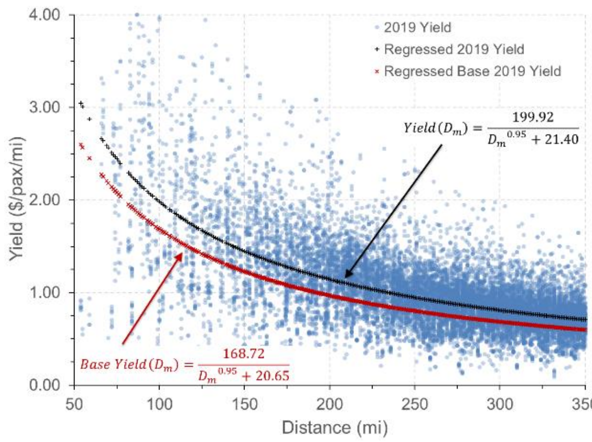


Figure 8: Yield and base yield for 35,900 nonstop and one-stop itineraries from 2019

We then leverage the *generalized cost of travel* which sums the cash expenditures associated with the door-to-door journey and the value of time or opportunity cost associated with spending time traveling [21]. The mathematical expression for the generalized cost of travel is given in Equation (1) where GC_m is the generalized cost of travel of mode m, C_m is the trip cash expenditures, VT is the individual value of time, and T_m is the trip time. Because we are focusing on business travelers, the value of time of travelers is estimated by averaging the hourly wages at the origin county and at the destination county [22].

$$GC_m = C_m + VT * T_m \tag{1}$$

2.6 Mode choice modeling

The generalized cost of travel is a simplified model that accounts for the time spent traveling and the cost of travel to predict the often-complex behavior of long-distance travelers. Other factors typically get into the decision-making process of travelers such as comfort, ability to work during the trip, schedule inconveniences, and security hassles. As a result, a probabilistic model is therefore introduced to account for the uncertainty related to factors not specified in this simple model [23]. The traveler utility is then assumed to be the sum of a linear combination of the generalized cost of travel and an error term following independent and identically distributed extreme value distributions. The utility is given in Equation 2, where U_m is the utility of mode m, ϵ_m is the random error, and α and β_m are constants to be calibrated.

$$U_m = \propto \cdot GC_m + \beta_m + \epsilon_m \tag{2}$$

Because we are only interested in the difference in utilities between the various transportation modes, a single β_m constant is introduced for the air transportation utility, and it is simply renamed β. Under these assumptions, the probability that a traveler selects the air travel mode is given by the multinomial logit model [23] and the probability is expressed using Equation 3.

$$P_{air} = \frac{1}{1 + e^{U_{car} - U_{air}}} \tag{3}$$

The calibration of the utility functions is performed next using a maximum likelihood technique which finds model parameters α and β which maximize the likelihood of the observed choices conditional on the model. In other words, the objective is to find the α and β that maximize the likelihood that the sample was generated from the model. The likelihood function in a binary choice setting is given by Equation 4 where *Y(m,i)* is an indicator function indicating if a passenger *i* selects transportation mode *m*, and *P(m,i)* is the probability that a passenger *i* chooses transportation mode *m*. The easier-to-manipulate log-likelihood function is given by Equation 5.

$$L(\alpha, \beta) = \prod_i P(m,i)^{Y(m,i)} \cdot \left(1 - P(m,i)\right)^{(1 - Y(m,i))} \tag{4}$$

$$l(\alpha, \beta) = ln\left(L(\alpha, \beta)\right) = \sum_i Y(m,i) \cdot ln\left(P(m,i)\right) + \left(1 - Y(m,i)\right) \cdot ln\left(1 - P(m,i)\right) \tag{5}$$

For each region under study and for all markets contained in the 2008 TAF, we calibrate the utility functions by finding the α and β values that maximize the log-likelihood indicator. The outcomes of these maximization exercises are given in Table 3 and Table 4 where the observed air market preference from 2008 is plotted against the estimate from our mode-choice model. While there is some dispersion around the fitted value, the model correctly captures the observed trends: markets where the air travel mode has a 0% market preference are properly captured and markets where the air travel mode has a 100% market preference are properly captured as well. The histograms of Table 4 represent the error in predicted air market preferences and confirm that the model is reasonable: for the seven regions under investigation, 80% of markets exhibit less than 20% market preference error. The utility model and corresponding mode choice are thus validated and can be applied to the 2040 demand dataset to forecast mode split once new regional air services are introduced.

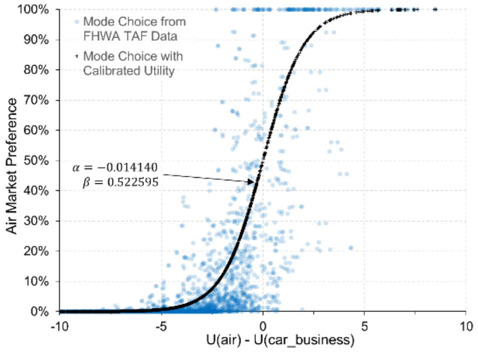
2.7 Predicting demand for regional air mobility services

With a mode-choice model that predicts the behavior of long-distance travelers, we can now estimate how many of these travelers would select regional air mobility services if these were offered. To do so, for each market, we first aggregate the demand for air transportation and the demand for auto-for-business transportation from the 2040 TAF forecast [13]. This yields the total demand that regional air mobility services could target (the behavior of auto-for-leisure travelers is much harder to predict as the reasons for travel can be very diverse and many factors will influence the mode choice such as number of travelers in party and time spent at destination). The outcomes of this prediction exercise are discussed in Section 3.

Table 3: Actual and predicted air market preferences in 2008

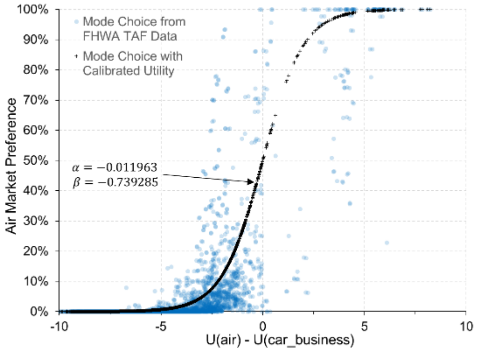
Pacific Northwest

(3,730 Markets)



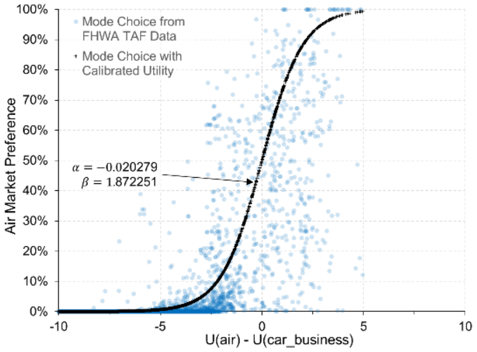
Northern Great Plains

(8,790 Markets)



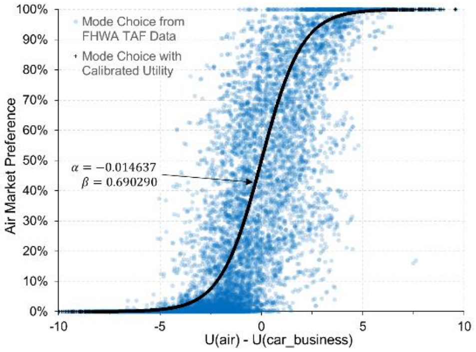
Midwest

(8,690 Markets)



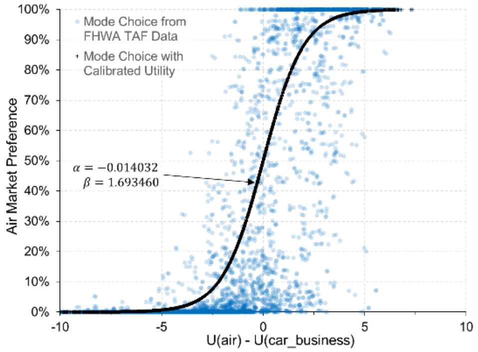
Northeast Corridor

(19,300 Markets)



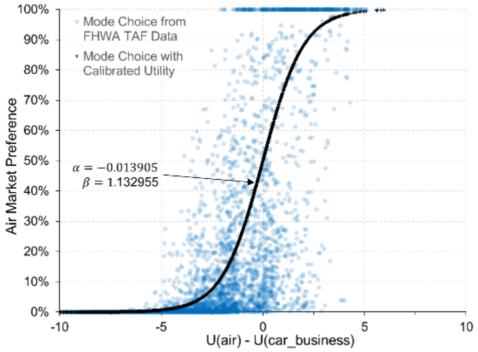
Southwest

(5,170 Markets)



Southern Great Plains

(5,930 Markets)



Southeast

(8,680 Markets)

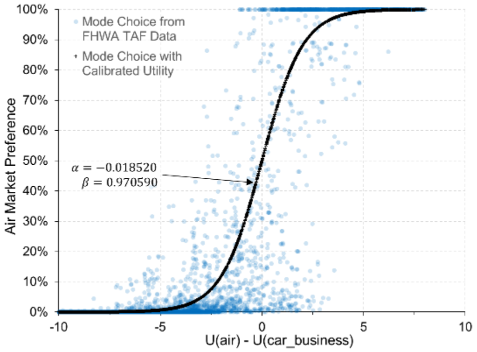
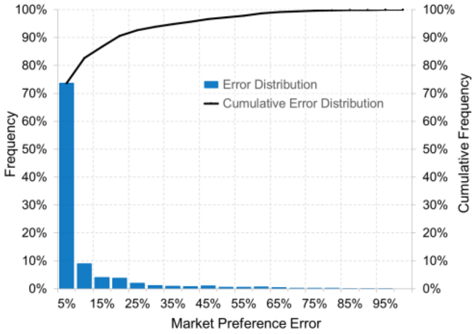


Table 4: Distribution of errors in air market preference predictions for 2008

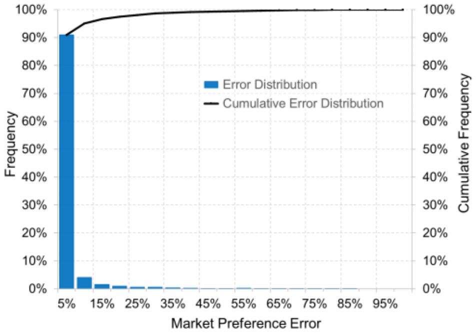
Pacific Northwest

(3,730 Markets)



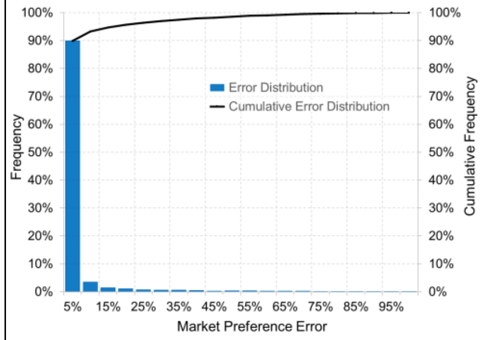
Northern Great Plains

(8,790 Markets)



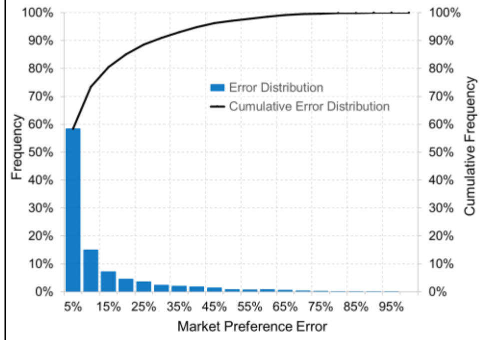
Midwest

(8,690 Markets)



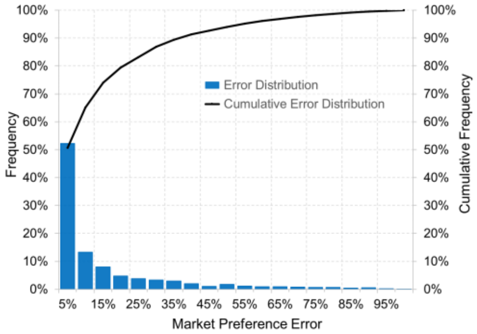
Northeast Corridor

(19,300 Markets)



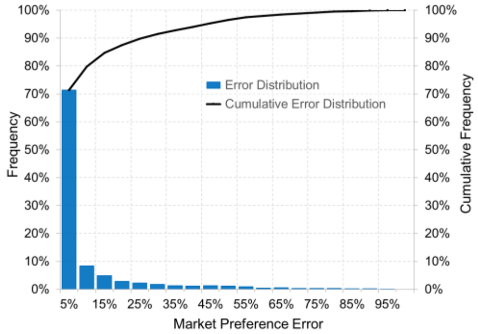
Southwest

(5,170 Markets)



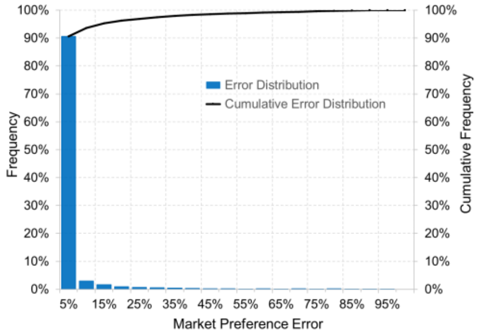
Southern Great Plains

(5,930 Markets)



Southeast

(8,680 Markets)



3. Regional Air Mobility Market Analysis

3.1 Anatomy of the markets of interest

The first outcome of the market analysis is a description of all county-to-county markets with distances ranging from 100 miles up to 350 miles and with an average daily demand between 10 and 75 passengers per day. This is provided in the figures of Table 5 for nonstop flights and Table 6 for connecting flights. The first striking observation, valid across all regions, is that there are many more markets with low demand volumes than markets with high demand volumes as indicated by the exponential decay shown by the frequency histograms along the vertical axes. While there are some markets with demand exceeding 50 passengers per day, the histograms indicate that most of the demand will be for thin routes that cannot support more than a few flights per day. This can be an issue for airlines as low volume routes are traditionally challenging to operate profitably.

One solution used by airlines to mitigate this challenge is to combine passengers at the origin and fly them to a hub to connect on another flight to their final destinations. This aggregation helps airlines offer connecting services where the demand is otherwise too low to offer nonstop services but reduces the attractivity of air services over short distances due to circuitous routings and airport latencies. This is indicated in the figures of Table 6 which show no blue hexagons in the top left corner of each graph. In fact, most of the markets with door-to-door distances shorter than 100 miles entirely vanish when nonstop services are no longer considered. This highlights that most of the shorter county-to-county markets disappear when connecting air services are the only options offered to air passengers.

3.2 Air mode market preferences

The second set of results describes the unconstrained market preference for air travels. This demand is called *unconstrained* because it is estimated before additional constraints related to flight schedules are introduced. The various figures of Table 7 and Table 8 highlight the preference of travelers for air travel as a function of the market distance and travel time savings for nonstop services and connecting services respectively. As expected, when distances increase, the market preference for air travel increases. For most markets, we see almost 100% market preference for air travels if the market exceeds 250 miles for nonstop services or 300 miles for connecting services. While the 250 miles threshold is valid across all regions for nonstop services, the 300 miles threshold varies slightly for connecting services: the Northern Great Plains and Southern Great Plains seem to transition to air travel at slightly longer distances (about 350 miles). This is likely due to the limited number of hubs available to connect and the resulting circuitous routings of connecting air services. The limited road congestion in these two regions may also be a contributing factor, as it makes automobile transportation more competitive.

The figures of Table 9 highlight the unconstrained market preference for air travels for both nonstop and connecting services for a few selected markets in each of the seven regions. For each region, 36 markets are sampled from 12 different distance categories. These markets are selected randomly and are plotted by door-to-door distance in ascending order. Three markets are sampled from each category, namely three from the 50–75-mile category, three from the 75-100-mile category, and so on, all the way to the 325-350-mile category. These lollipop graphs help visualize the additional demand that can be captured once nonstop point-to-point services are offered to travelers. There are a few markets where the nonstop and connecting market preferences are identical, and this occurs when air transportation is the preferred option regardless of the number of connections.

Table 5: Bivariate distribution with air travel demand and door-to-door direct distance for nonstop services

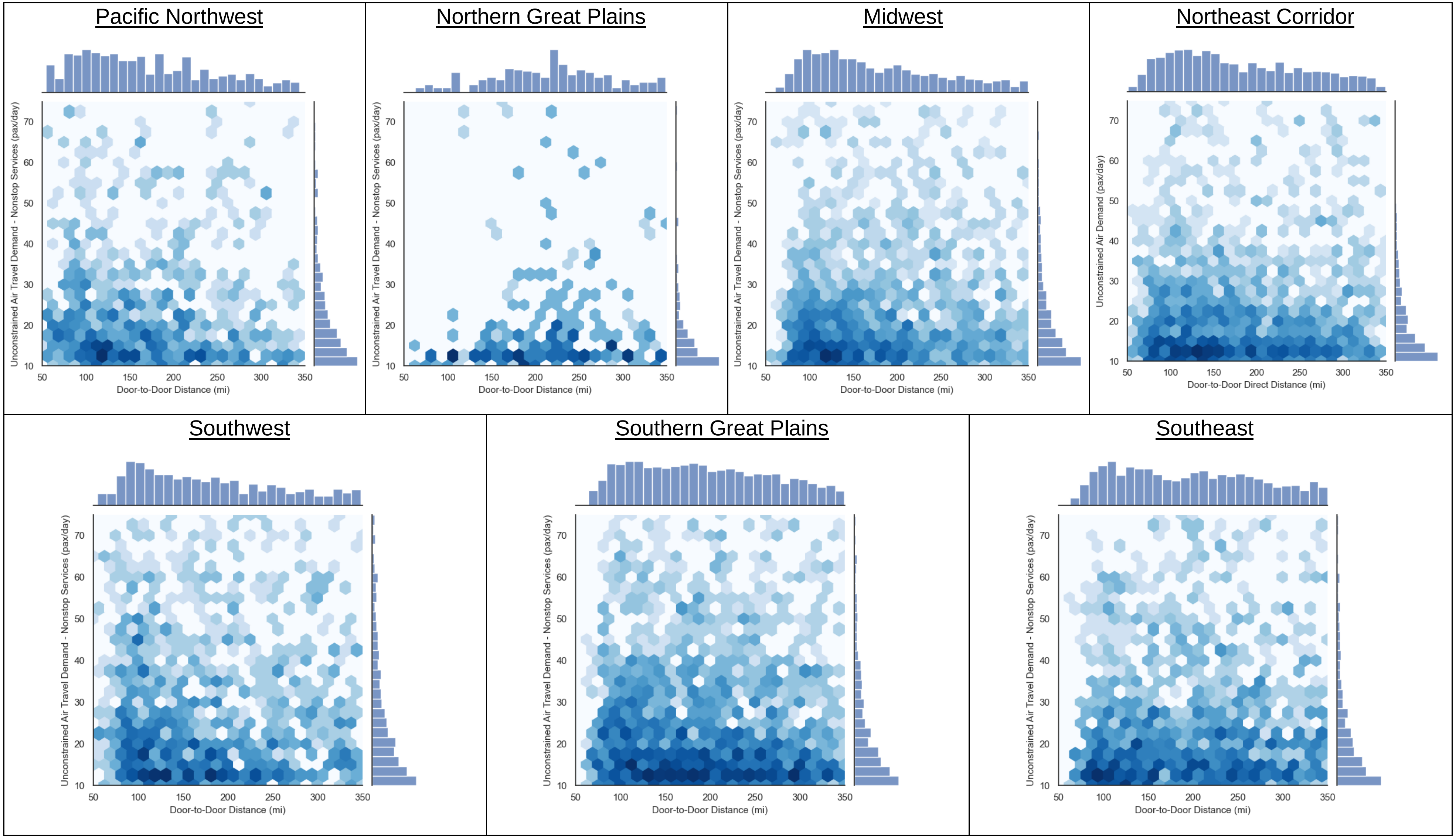


Table 6: Bivariate distribution with air travel demand and door-to-door direct distance for connecting services

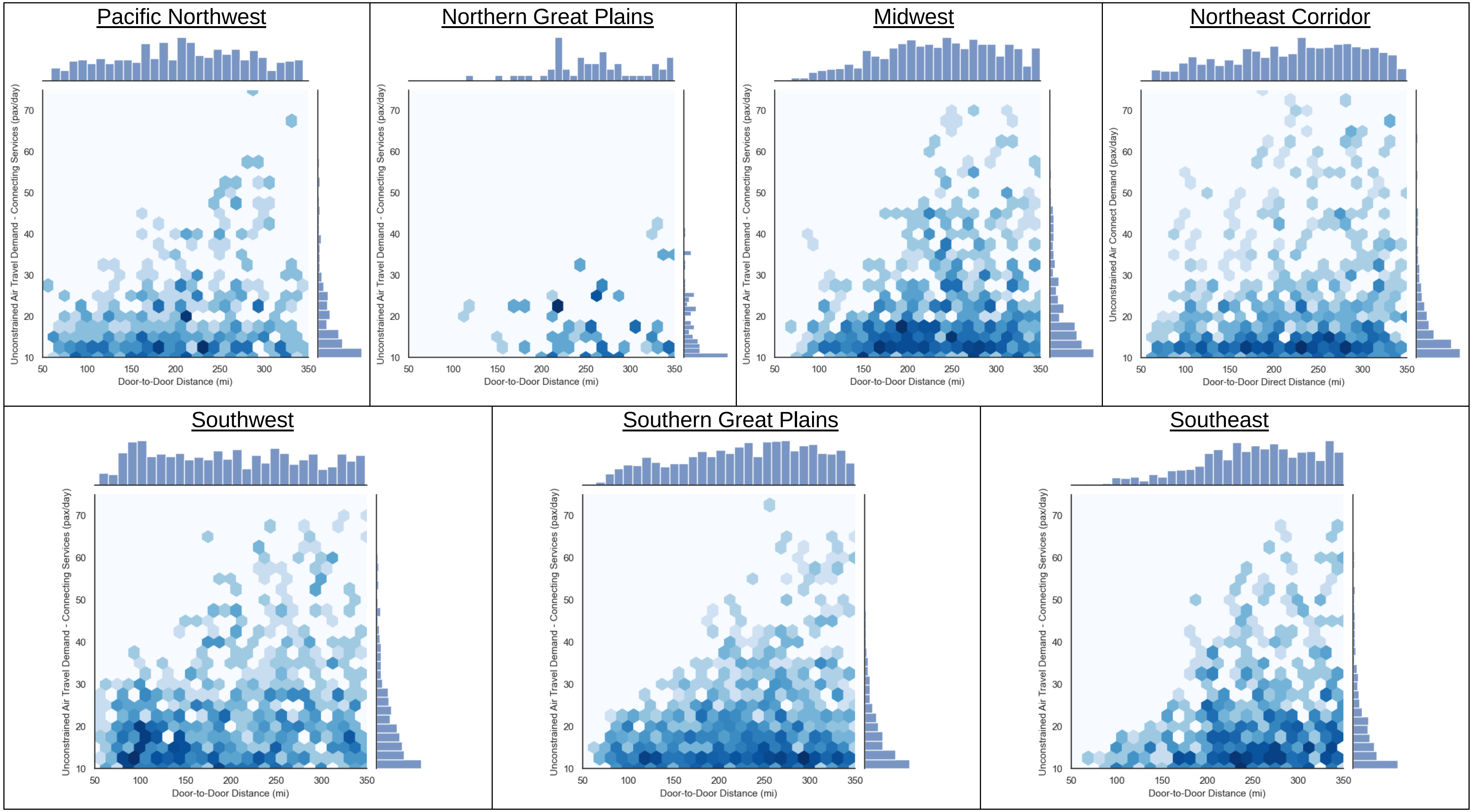
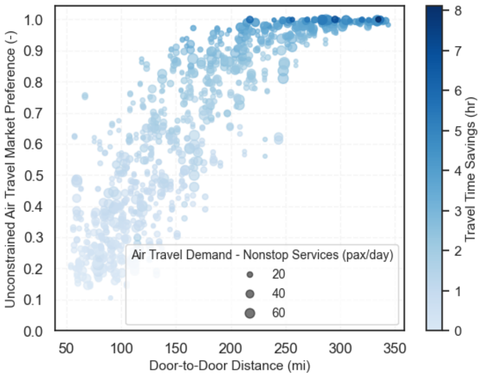
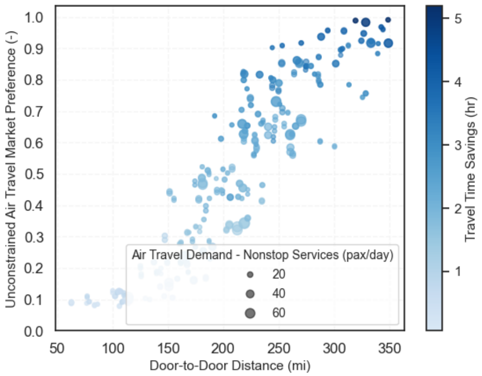


Table 7: Air market preferences for nonstop services versus door-to-door great circle distance

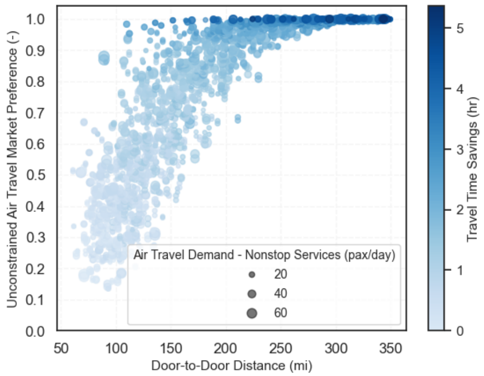
Pacific Northwest



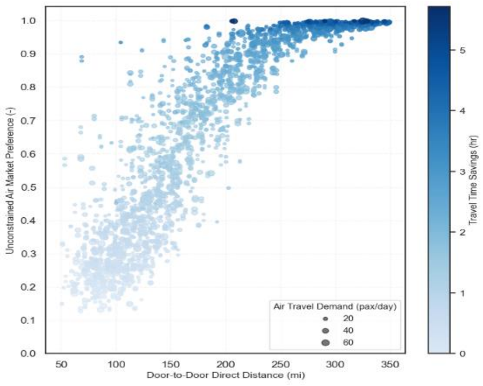
Northern Great Plains



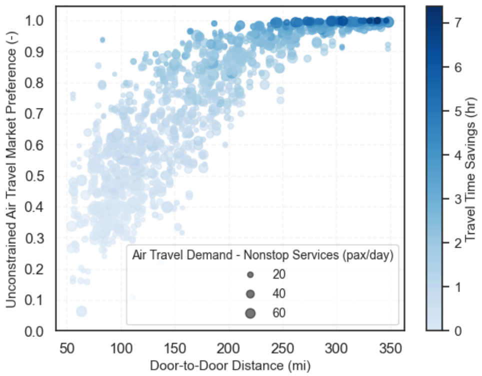
Midwest



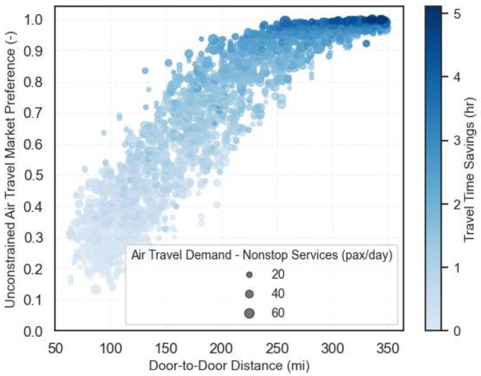
Northeast Corridor



Southwest



Southern Great Plains



Southeast

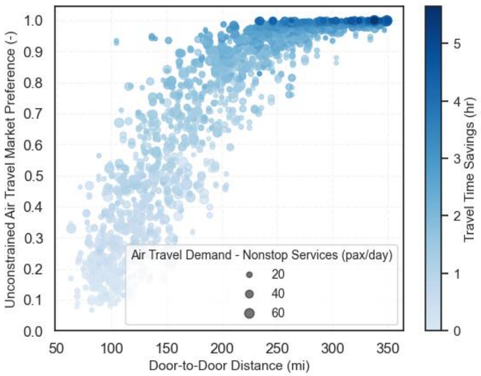
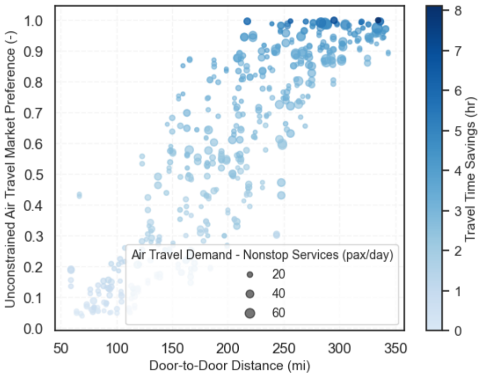
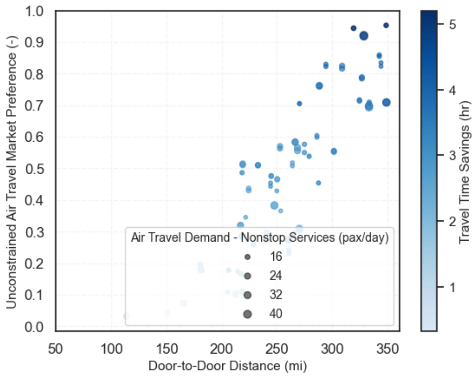


Table 8: Air market preferences for connecting services versus door-to-door great circle distance

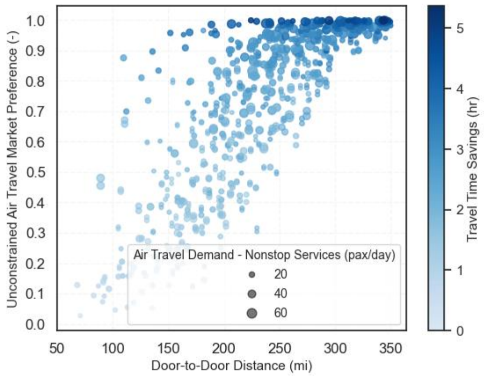
Pacific Northwest



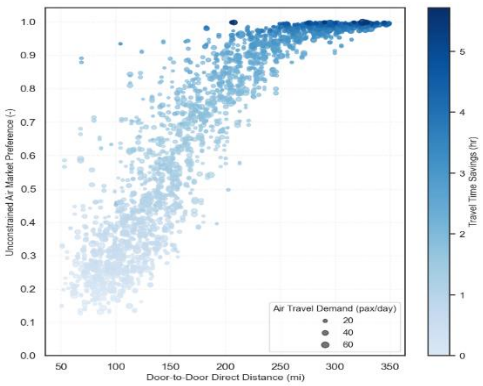
Northern Great Plains



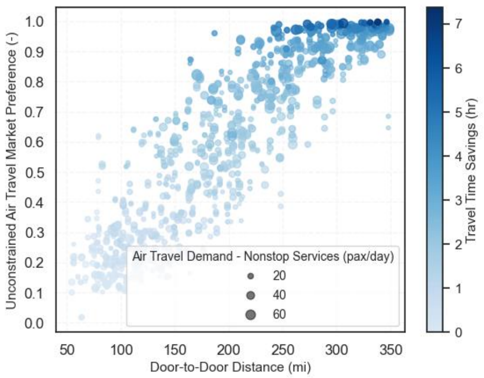
Midwest



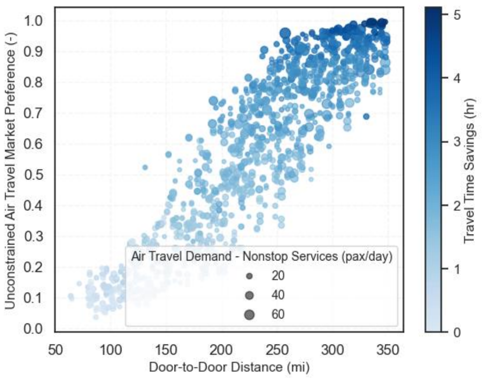
Northeast Corridor



Southwest



Southern Great Plains



Southeast

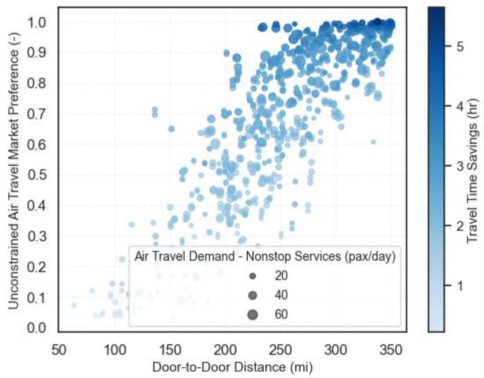
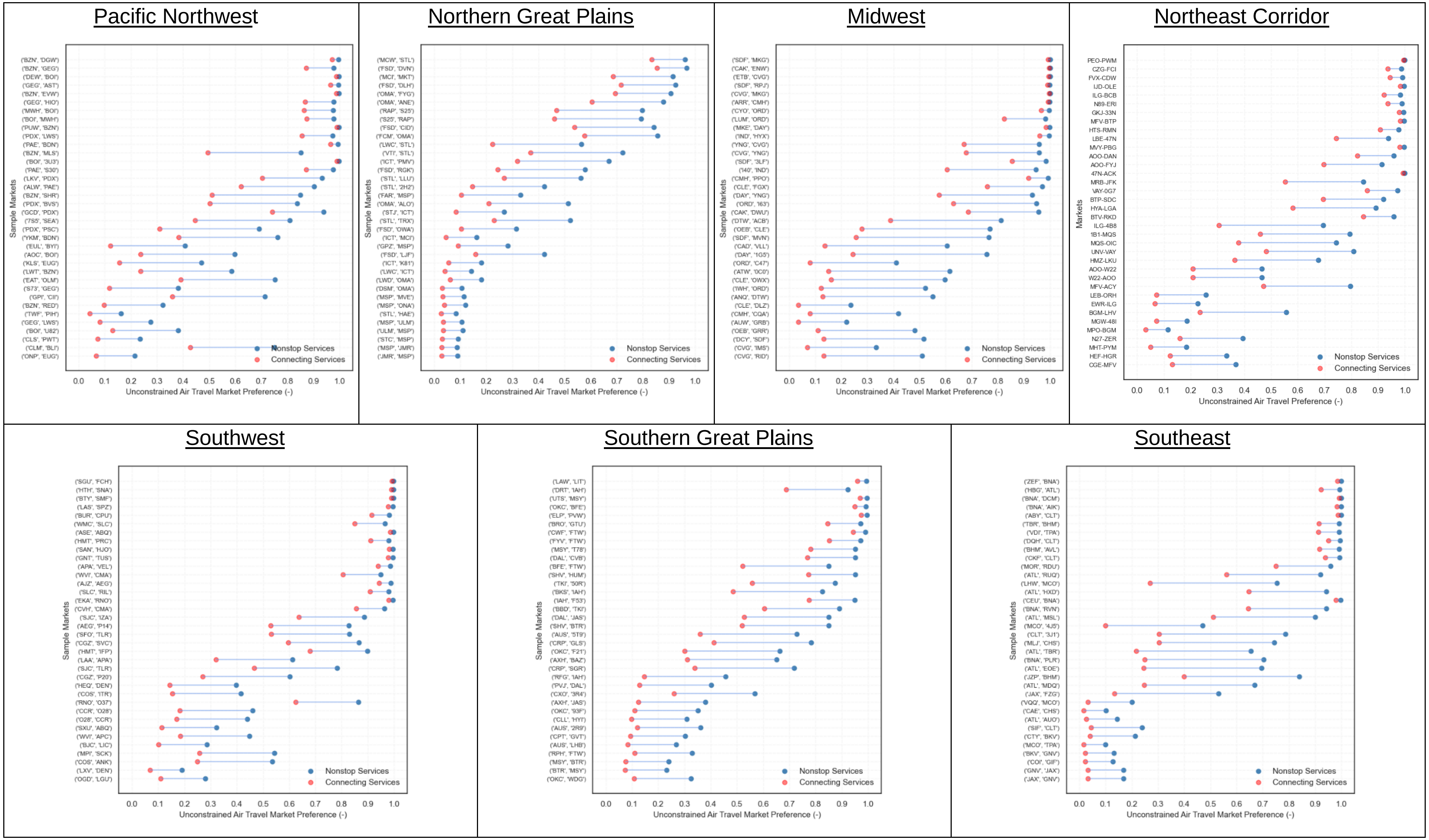


Table 9: Market preference for nonstop and connecting regional air mobility services for a sample of markets in each region of interest



3.3 Auto-to-air switching rates

The third set of results highlights the added value brought by the introduction of regional air mobility services in the National Airspace System. The figures of Table 10 and Table 11 depict switching rates as a function of market distance and travel time savings for nonstop services and connecting services respectively. Switching rates are defined as the fraction of long-distance travelers that were expected to drive in the 2040 TAF survey from the FHWA but that end-up flying once more convenient regional air mobility services are offered from convenient regional airports. For instance, a switching rate of 100% for a given market indicates that all travelers who are currently driving switch to air travel once regional air mobility services are offered from an airport close to their origin to an airport close to their destination.

As expected, switching rates increase as distances increase and this is highlighted by the sigmoid shape of most of the figures of Table 10 and Table 11. Similarly, the lighter colored bubbles at the lower end of the sigmoid curves indicate that limited travel time savings are achieved for shorter distances, and this is not conducive to high switching rates. In contrast, the darker colored bubbles at the higher end of the sigmoid curves indicate that significant travel time savings are achieved, and this is conducive to high switching rates.

Finally, there are lines of points along the horizontal axis and corresponding to a zero-switching rate. Each of these lines is made of two clusters, one corresponding to shorter distances and one corresponding to longer distances. The cluster of zero-switching rate points at shorter distances indicates that the distances are just too short for regional air mobility to be a valuable proposition. The cluster of zero-switching rate points at longer distances represents markets that are long enough that all travelers were already expected to fly using commercial air services in the original TAF forecast. Therefore, there are zero additional long-distance travelers to capture. This can be seen again in the vertical lines present in the various figures of Table 12, which compare the switching rates for both nonstop and connecting regional air mobility services. As expected, these figures highlight that the switching rates of nonstop flights is always greater than the switching rates of connecting flights for a given distance.

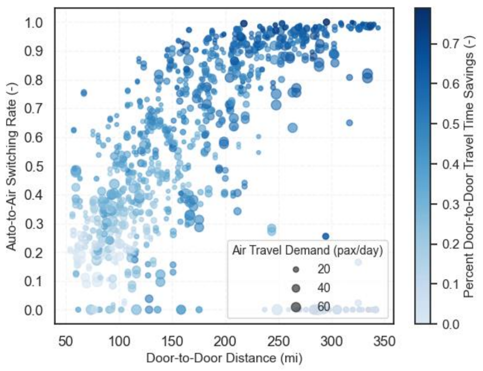
3.4 Promising markets

Table 13 provides some statistics as well as visual representations of the various markets uncovered. Each line represents one airport-to-airport market for which the average daily demand is greater than 10 passengers per day and less than 75 passengers per day. The lower limit of 10 passenger per day corresponds to the minimum daily passenger volume required for airlines to bid for Essential Air Services subsidies [24]. The upper limit of 75 passengers per day is arbitrary and corresponds to the capacity beyond which larger regional jets, such as the ubiquitous and more capable Embraer 170 and Bombardier CRJ700 jets flying for large regional airlines, are likely to be more appropriate. The objective of regional air mobility is not to compete with these existing large regional airlines, but rather to supplement them for thin markets over short distances.

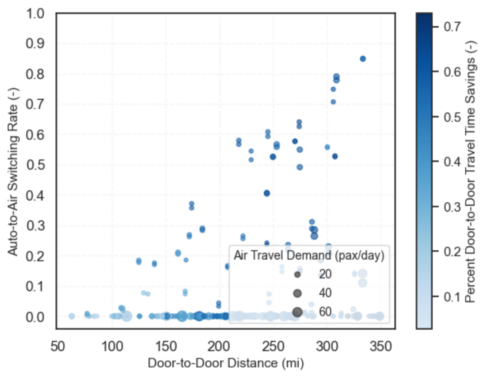
All in all, our analyses indicate that there is significant demand for regional air mobility services: we are able to identify over 13,000 airport-pairs with a combined demand exceeding 248,000 passengers across the entire United States. While this is less than the 2.9 million passengers transported everyday by scheduled air services across the United States, this represents nonetheless remarkable business opportunities for commuter operators and smaller regional airlines alike [25].

Table 10: Auto to nonstop regional air mobility services switching rate as a function of direct door-to-door distance. Size of bubble indicates volume; color indicates travel time savings.

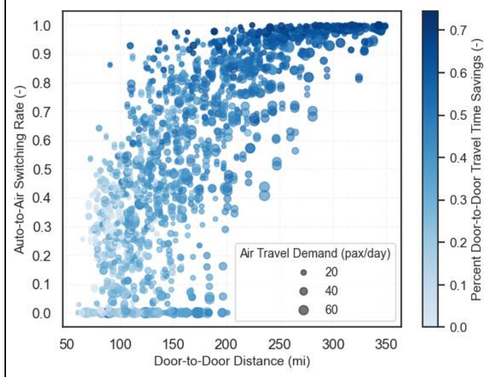
Pacific Northwest



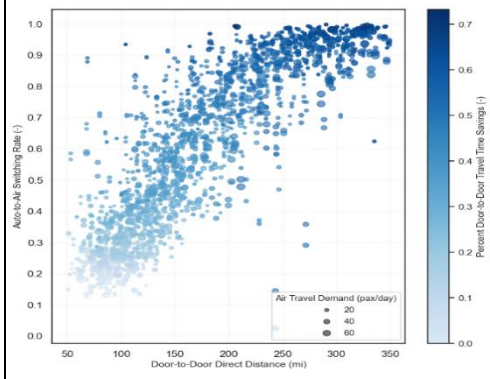
Northern Great Plains



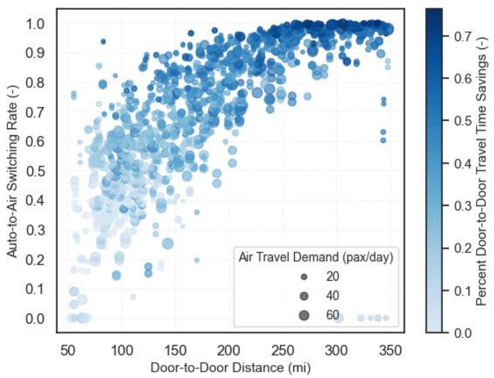
Midwest



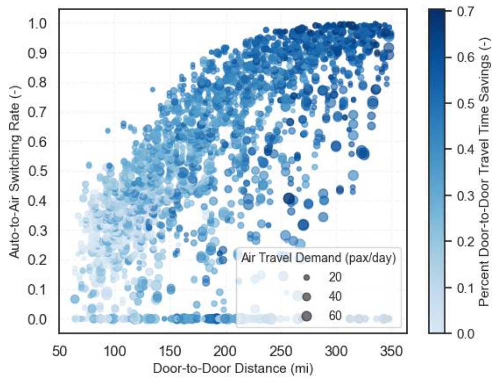
Northeast Corridor



Southwest



Southern Great Plains



Southeast

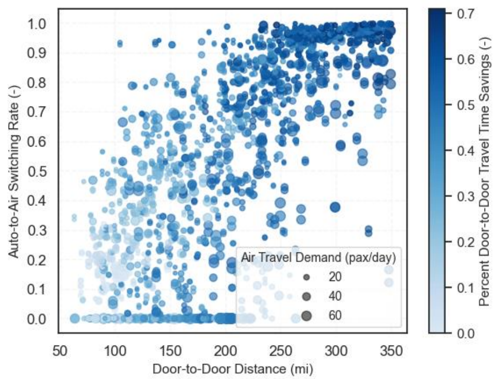


Table 11: Auto to connecting regional air mobility services switching rate as a function of direct door-to-door distance. Size of bubble indicates volume; color indicates travel time savings.

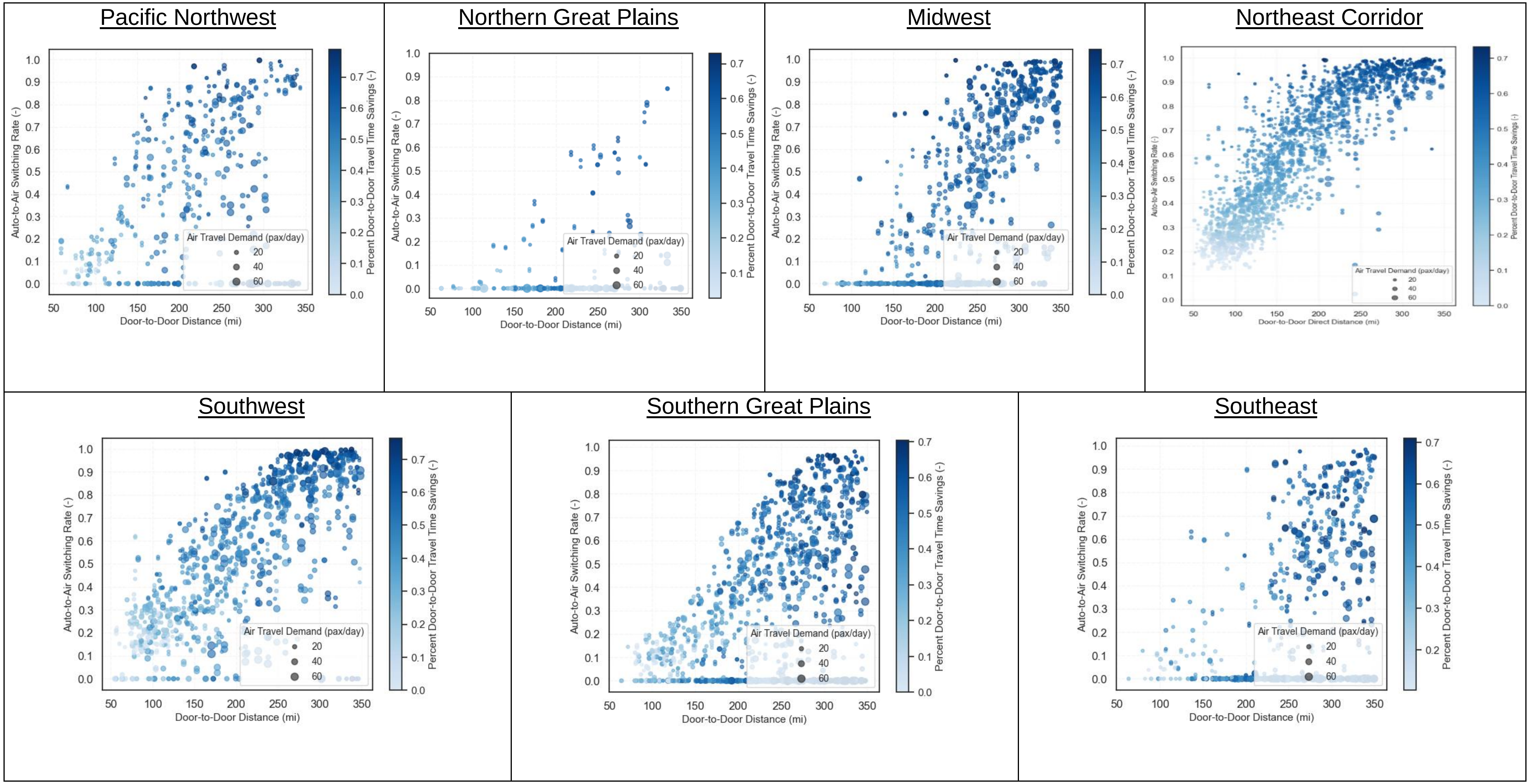
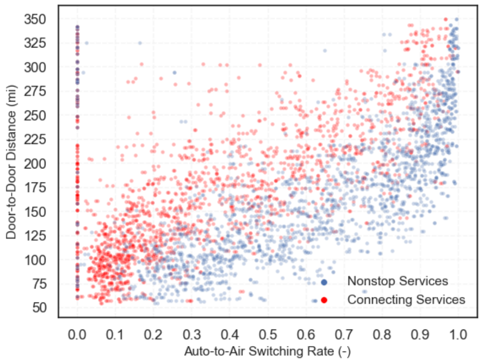
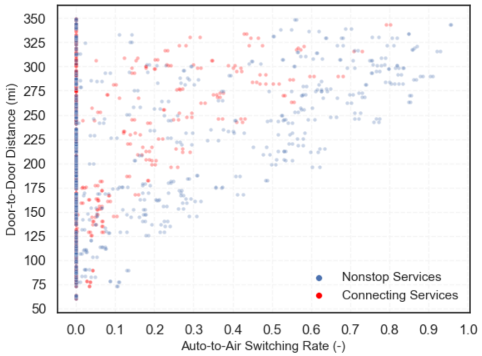


Table 12: Comparison of auto-to-air switching rates for nonstop and connecting regional air mobility markets

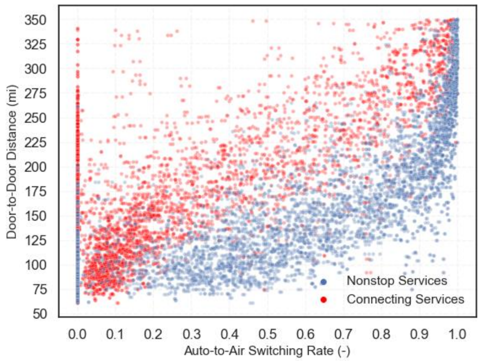
Pacific Northwest



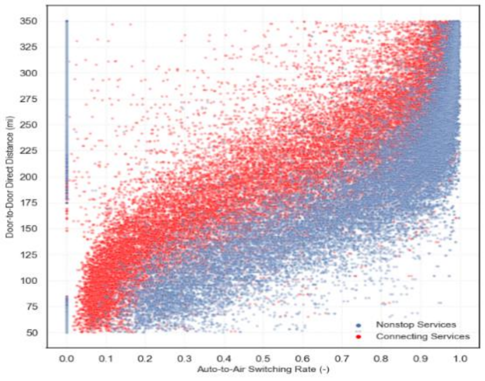
Northern Great Plains



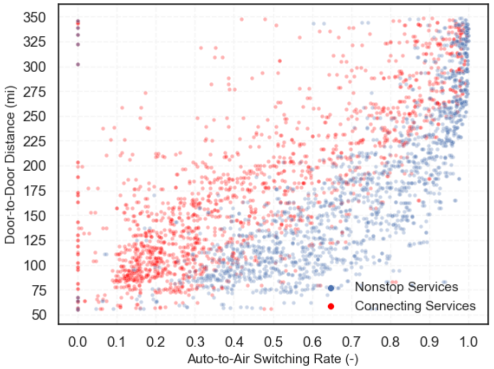
Midwest



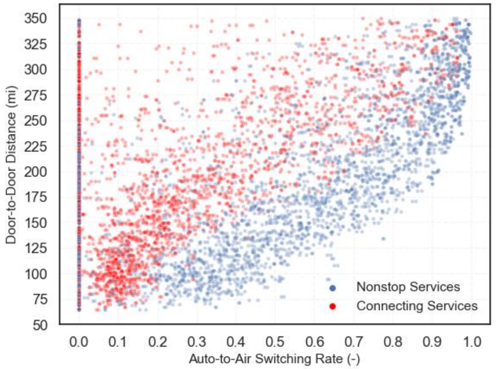
Northeast Corridor



Southwest



Southern Great Plains



Southeast

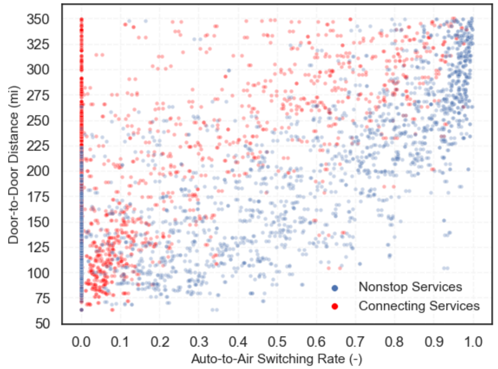
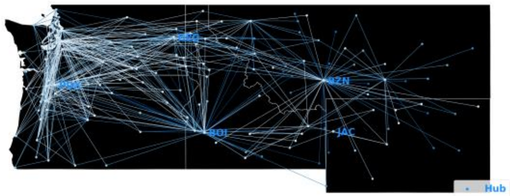


Table 13: Markets with distance greater than 100 miles and shorter than 350 miles, and with average demand between 10 passengers per day and 75 passengers per day

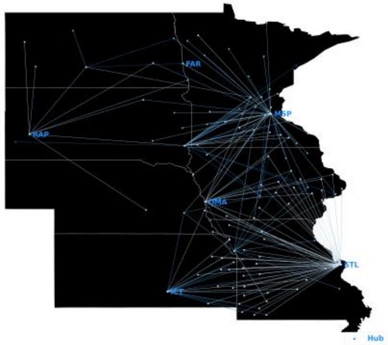
<u>Pacific Northwest</u>

Number of Markets (-): 1,077
Nonstop Demand (pax/day): 25,312
Connecting Demand (pax/day): 13,734



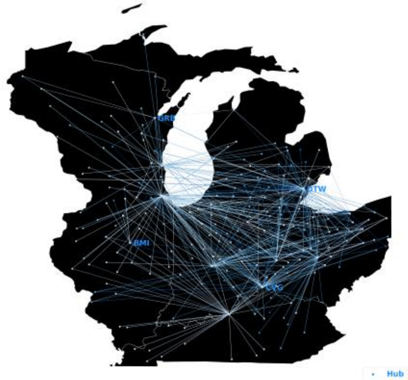
<u>Northern Great Plains</u>

Number of Markets (-): 334
Nonstop Demand (pax/day): 6,659
Connecting Demand (pax/day): 3,138



<u>Midwest</u>

Number of Markets (-): 2,426
Nonstop Demand (pax/day): 55,145
Connecting Demand (pax/day): 28,757

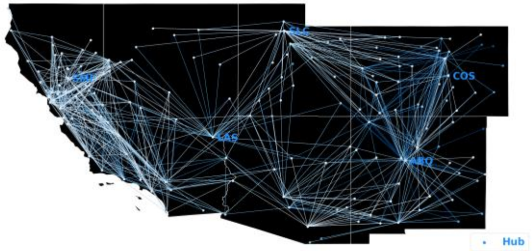


<u>Northeast Corridor</u>

Number of Markets (-): 2,463
Nonstop Demand (pax/day): 52,802
Connecting Demand (pax/day): 29,753

<u>Southwest</u>

Number of Markets (-): 1,685
Nonstop Demand (pax/day): 45,299
Connecting Demand (pax/day): 28,905

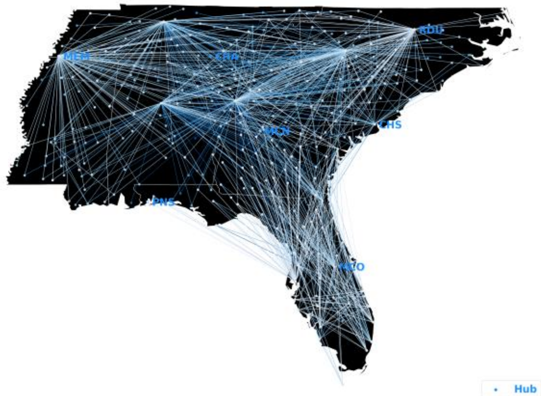


<u>Southern Great Plains</u>

Number of Markets (-): 2,922
Nonstop Demand (pax/day): 70,944
Connecting Demand (pax/day): 39,146

<u>Southeast</u>

Number of Markets (-): 2,162
Nonstop Demand (pax/day): 51,552
Connecting Demand (pax/day): 26,055



3.5 Demand for 19-seat aircraft gauge

In the rest of this paper, we retain only airport-to-airport markets with a demand between 10 and 50 passengers per day as we are not considering larger turboprops and focus on the 19-seat aircraft gauge. The updated upper limit of 50 passengers per day is again arbitrary and corresponds to more than twice the capacity of the 19-seat category, beyond which a larger 30-seat aircraft gauge might be more appropriate. Some statistics as well as some visual representations of the demand for this subset of the markets identified previously are given in Table 15.

So far, we have uncovered significant demand for regional air mobility services that is currently mostly unmet by commuter operators. Despite promising, this may still be insufficient to support profitable operations: for regional air mobility operations to thrive, passengers need to be transported profitably and there are many implications to this statement. We highlight a few below:

- Profitable operations means that airfares offered on each market need to be sufficiently high to cover the direct and indirect costs of operations.
- Profitable operations means that the operating costs need to be low-enough to allow operators to offer affordable airfares and stimulate the demand for air travels.
- Profitable operations means that the operating network must be sufficiently interconnected to ensure that aircraft can operate flights without the need for costly repositioning flights.
- Profitable operations means that the schedule of flights must be done to ensure that most of the demand can be captured, and that aircraft can operate as many flights as possible. Indeed, high aircraft utilization allows operators to spread fixed costs over many passenger-miles and thus decrease the cost per available seat mile.

We thus perform a system-of-system study to understand how large the 19-passenger aircraft market is. As part of this study, the network and the schedule of flights are both optimized to maximize profits to the operator. We follow the approach detailed in Justin et al. [14]. A mixed integer linear programming approach is used and some of the underlying assumptions are summarized in Table 14. The airfares used to estimate passenger revenue follow the regression of the base yields detailed in Figure 8. The 19-passenger aircraft model used to estimate operating costs is a notional hybrid-electric variant of the Beechcraft 1900D developed for the NASA EPFD program by Georgia Tech and detailed in Cai et al [26].

Table 14: Main network and schedule optimization assumptions

Passenger airport ingress (min)	25	Route maximum permitted mileage (-)	1.5
Passenger airport egress (min)	10	Aircraft turnaround time (min)	20
Passenger minimum connect time (min)	25	Jet-fuel price ($/gal)[1]	2.98
Passenger maximum connect time (min)	85	Electricity price (c/kWh)[2]	14.5

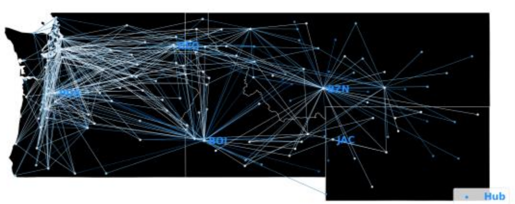
The outcome of this system-level study is provided in the regional maps of Table 16. The figures depict, for each region, the markets that can be profitably served by future regional air mobility operators. Except for the Northern Great Plains, these networks are substantial and attest not only to the massive underlying demand but also to the business opportunities that exist. It is not entirely clear why the Northern Great Plains region is unable to support more operations, but the authors hypothesize that the geographical location of hubs retained for this analysis may not be optimal. Indeed, several of them (MSP, STL) are located at the border of the study-region making them unattractive for regional connections, especially when a maximum permitted mileage constraint of 150% is enforced.

[1] IATA Jet Fuel Price Monitor, www.iata.org/en/publications/economics/fuel-monitor, retrieved February 2022
[2] Power Optimized Battery Swap and Recharge Strategies for Electric Aircraft Operations, Justin, Payan, Briceno, German, Mavris, Transportation Research Part C: Emerging Technologies, vol115, 2021

Table 15: Markets with distance greater than 100 miles and shorter than 350 miles, and with average demand between 10 passengers per day and 50 passengers per day

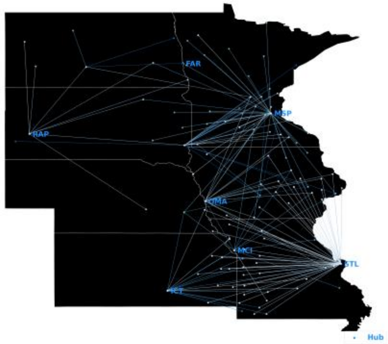
Pacific Northwest

Number of Markets (-): 987
Nonstop Demand (pax/day): 19,847
Connecting Demand (pax/day): 10,740



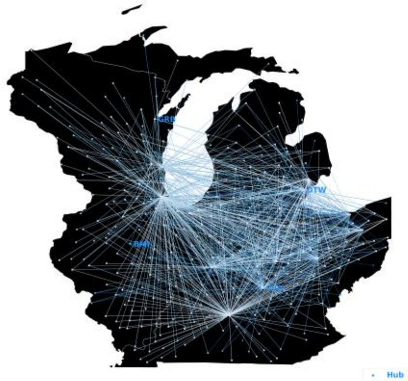
Northern Great Plains

Number of Markets (-): 318
Nonstop Demand (pax/day): 5,623
Connecting Demand (pax/day): 2,749



Midwest

Number of Markets (-): 2,275
Nonstop Demand (pax/day): 45,864
Connecting Demand (pax/day): 23,393

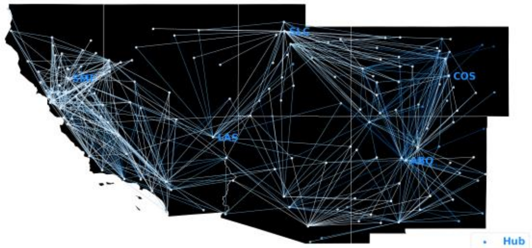


Northeast Corridor

Number of Markets (-): 2,332
Nonstop Demand (pax/day): 44,781
Connecting Demand (pax/day): 24,822

Southwest

Number of Markets (-): 1,489
Nonstop Demand (pax/day): 33,313
Connecting Demand (pax/day): 21,140



Southern Great Plains

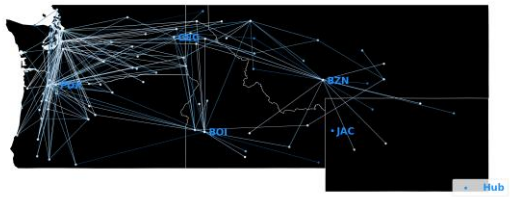
Number of Markets (-): 2,680
Nonstop Demand (pax/day): 56,309
Connecting Demand (pax/day): 31,101

Southeast

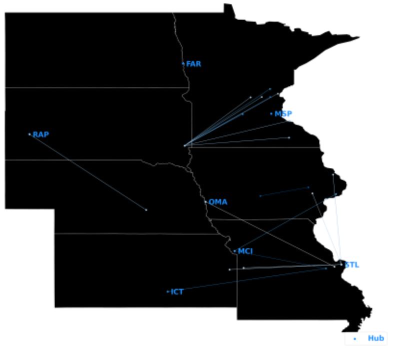
Number of Markets (-): 1,985
Nonstop Demand (pax/day): 40,752
Connecting Demand (pax/day): 20,538

Table 16: Markets served using 19-seat aircraft to fly regional air mobility operations

Pacific Northwest



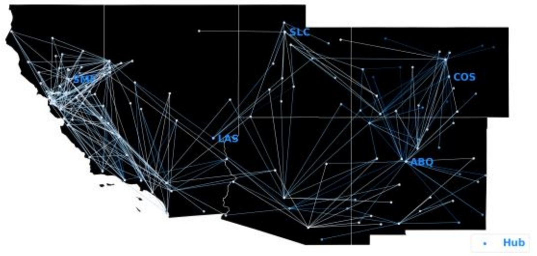
Northern Great Plains



Midwest

Northeast Corridor

Southwest



Southern Great Plains

Southeast

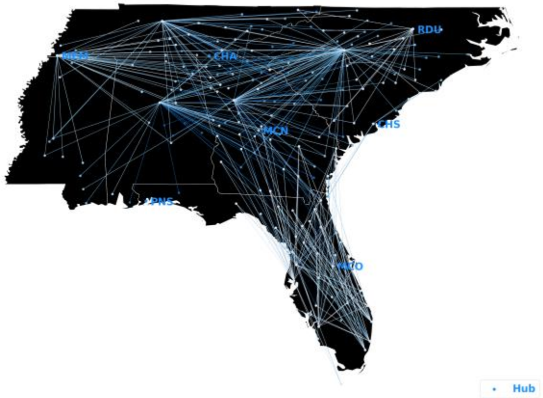
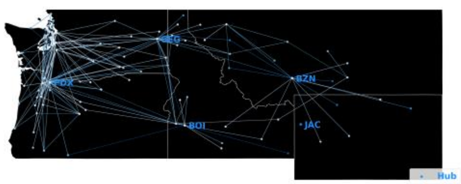
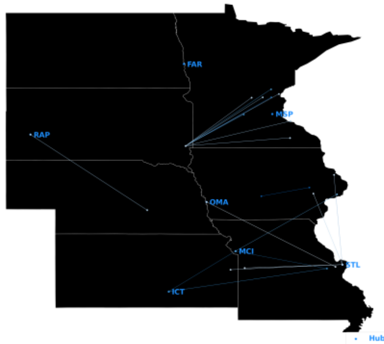


Table 17: Network of flights operated by 19-seat aircraft for regional air mobility services

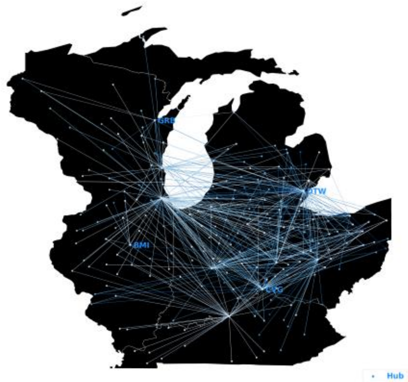
Pacific Northwest



Northern Great Plains

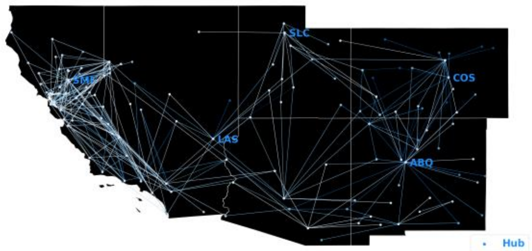


Midwest



Northeast Corridor

Southwest



Southern Great Plains

Southeast

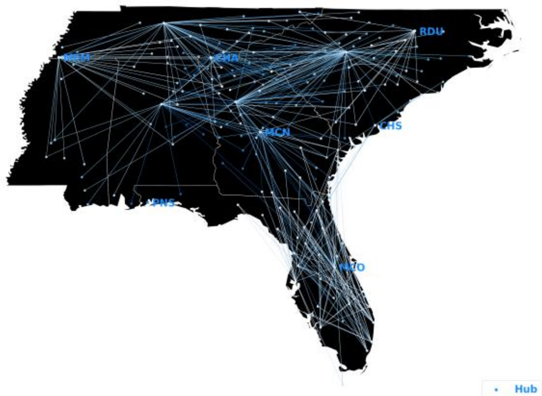
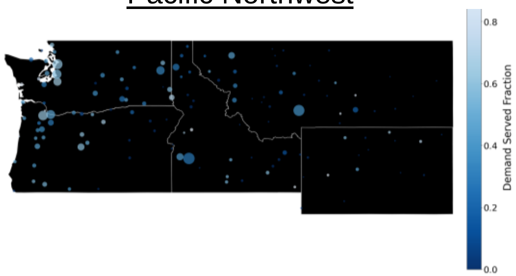
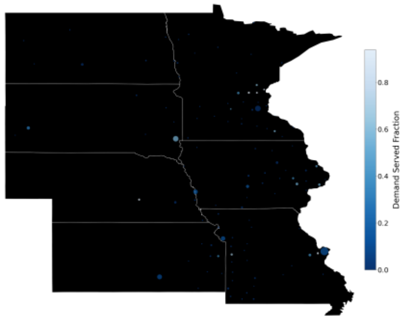


Table 18: Percentage of the regional air mobility passenger demand served using fleet of 19-seat aircraft, aggregated by origin airport

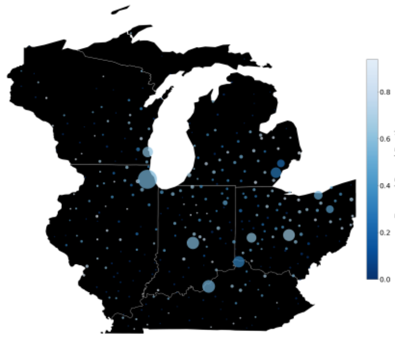
Pacific Northwest



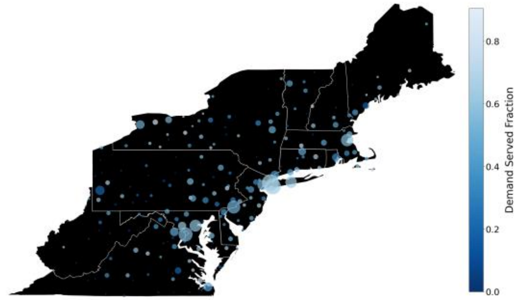
Northern Great Plains



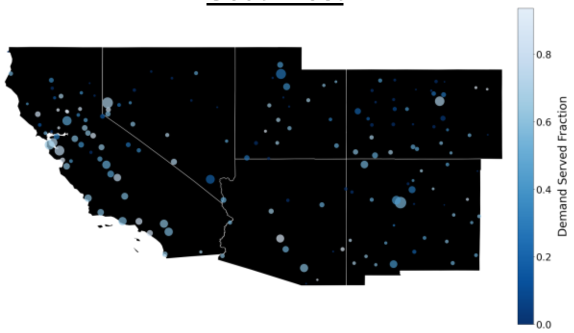
Midwest



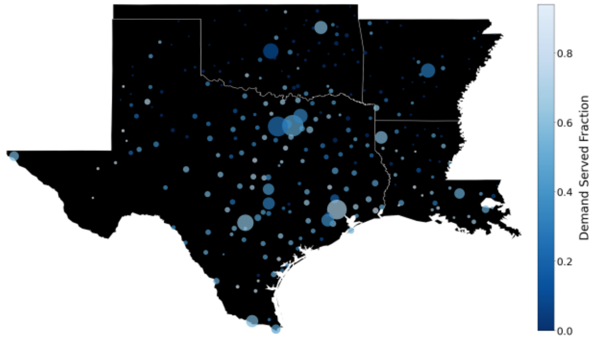
Northeast Corridor



Southwest



Southern Great Plains



Southeast

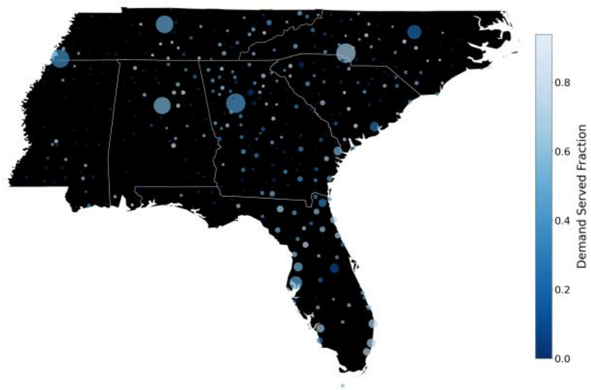


Table 19: Regional air mobility network & operations statistics using a fleet of 19-seat aircraft

	Pacific Northwest	Northern Great Plains	Midwest	Northeast Corridor
Daily passengers carried (-):	6,779	1,014	19,161	17,173
Passenger carried fraction (-):	41%	19%	49%	51%
Nonstop passenger fraction (-):	83%	99%	80%	61%
Daily passenger-mile (pax.mi):	1,224,300	245,666	3,873,822	3,793,176
Daily flights number (-):	698	97	1,796	1,714
Load factor (-):	59%	55%	69%	74%
Airports served (-):	84	24	214	146
Airports served fraction (-):	59%	20%	62%	73%
Markets served (-):	350	35	846	962
Markets served fraction (-):	35%	11%	37%	41%
Fleet size (-):	186	25	582	533
Yearly utilization (hr):	1,295	1,602	960	975
Avg. door-to-door time (hr):	2:19	2:06	2:07	2:49
Avg. travel time savings (-):	44%	56%	46%	40%
Optimization MIP Gap (-):	4%	4%	4%	4%

	Southwest	Southern Great Plains	Southeast
Daily passengers carried (-):	12,355	18,560	15,863
Passenger carried fraction (-):	51%	43%	45%
Nonstop passenger fraction (-):	90%	86%	84%
Daily passenger-mile (pax.mi):	2,483,338	4,054,497	3,426,412
Daily flights number (-):	1,139	1,685	1,515
Load factor (-):	63%	66%	65%
Airports served (-):	128	187	201
Airports served fraction (-):	73%	64%	55%
Markets served (-):	525	842	673
Markets served fraction (-):	35%	31%	34%
Fleet size (-):	361	547	472
Yearly utilization (hr):	1,055	1,066	1,080
Avg. door-to-door time (hr):	2:18	2:20	2:14
Avg. travel time savings (-):	43%	43%	55%
Optimization MIP Gap (-):	4%	4%	4%

The regional maps of Table 17 highlight the network of flights that needs to be operated to serve these markets. While broadly similar to the regional maps of Table 16, the differences reflect the choice of nonstop or connecting flights to serve each market. The regional maps of Table 18 highlight the various airports served as well as the fraction of the demand served. For these figures, the size of the bubbles is commensurate with the volume of passengers originating at that airport, while the shade of blue represents the fraction of the originating demand met. For many of these airports, 50% or more of the local demand is met with the introduction of regional air mobility services as indicated by the lighter shades of blue.

Finally, the data in Table 19 provides various statistics regarding operations in the various regions. All in all, regional air mobility services reach over 980 airports across the United States compared to the 526 currently receiving commercial air services [5]. Of particular interest is the fleet size which exceeds 2,700 units. While this represents a staggering opportunity for aircraft manufacturers, it is important to emphasize that this number assumes that the entirety of the regional air mobility market with demand between 10 and 50 passengers is met with 19-seat aircraft. Realistically, other aircraft gauges such as 9-seaters and 30-seaters will also compete for a share of this market.

3.6 Demand for 19-seat aircraft gauge in the presence of competing aircraft gauges

For the final set of analyses, a fleet including competing aircraft gauges is introduced. A smaller aircraft based on the Tecnam P2012, seating 9 passengers, and featuring a fully electric powertrain and distributed electric propulsion is introduced, along with a larger aircraft based on the Embraer 120, seating 30 passengers, and featuring a hybrid-electric powertrain. All three aircraft are comparable technology-wise and are infused with similar sets of technologies expected to be available by 2040. The fully electric 9-seat aircraft is range-limited owing to the limited energy density of batteries and can fly up to 170 mi with reserves (58 mi diversion and 45 min thereafter). Both the 19-seat and 30-seat hybrid-electric aircraft have ranges in excess of 350 mi with reserves (58 mi diversion and 45 min thereafter). More details about the design and performance characteristics of these vehicles are provided in Morejón et al. [26].

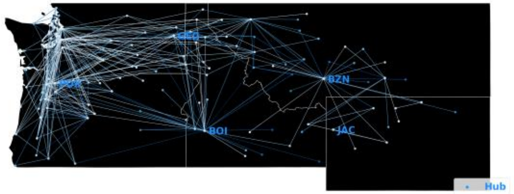
The outcome of this system-level optimization is provided in the regional maps of Table 20. The figures depict, for each region, the markets that can be profitably served by future regional air mobility operators using a mix of 9-seat, 19-seat, and 30-seat aircraft. As expected, the network appears denser and more complete than previously. This is not surprising since we have added two aircraft gauges that introduce more flexibility during the schedule and network optimization. Indeed, the addition of a smaller aircraft gauge helps reach profitably some of the lower demand markets.

The regional maps of Table 21, Table 22,Table 23, and Table 24 depict the networks operated by the subfleets of 9-seat, 19-seat, and 30-seat aircraft. Despite transporting many more passengers network-wide, the size of the subfleet of 19-seaters is decreasing quite dramatically across all regions (some regions exhibit drops exceeding 70%). Across the entire United States, the fleet size drops from 2,706 units to 1,481 units which corresponds to a 45% reduction in subfleet size. Looking closely at the markets still operated by the 19-seater, we observe that most of the routes remaining correspond to routes beyond the range of the electric 9-seat aircraft. With a few exceptions, it appears that 19-seat aircraft are displaced by the more efficient 9-seat aircraft on flights within the range of the electric 9-seater.

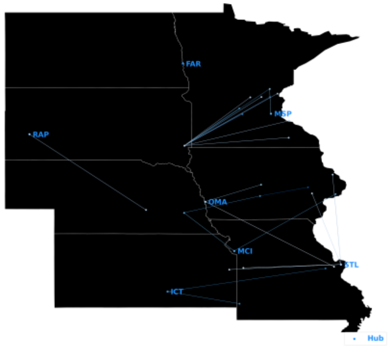
Finally, Table 25 provides a few summary statistics about the network and the schedule of the operations with the new fleet mix. As previously mentioned, all metrics highlight some significant improvements whether it is measured by the number of passengers carried (110,634 passengers or +21%), by the number of cities served (1,225 airport served or +25%), by the number of markets served (5,921 airport-pairs or +62%), or by the load factors.

Table 20: Markets served using a fleet of 9-seat, 19-seat, and 30-seat aircraft to fly regional air mobility services

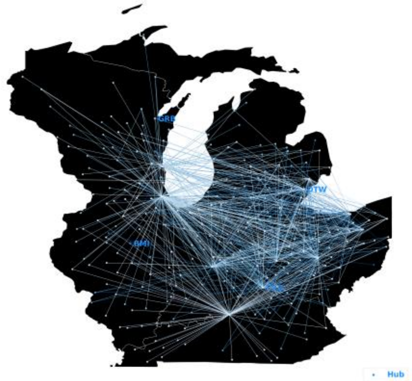
Pacific Northwest



Northern Great Plains

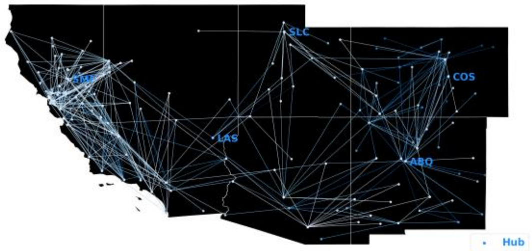


Midwest



Northeast Corridor

Southwest



Southern Great Plains

Southeast

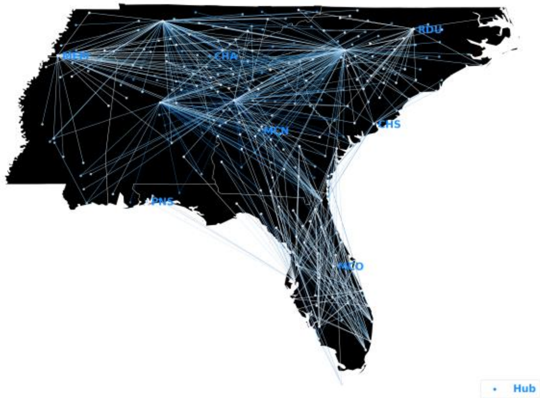
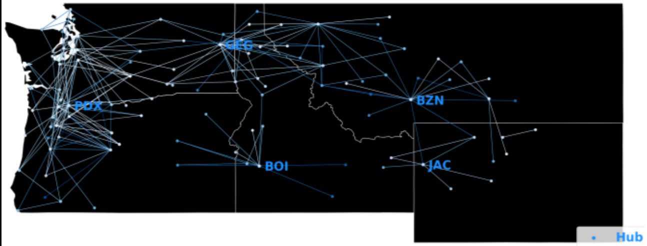


Table 21: Network of flights operated by the fleet of 9-seat, 19-seat, and 30-seat aircraft in the Pacific Northwest and Northern Great Plains for regional air mobility services

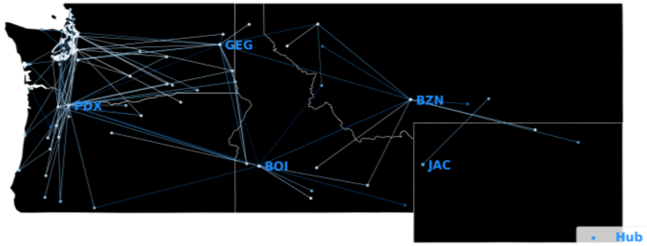
<u>9-Seat</u>

Fleet Size (-): 293
Number of Flights (-): 939
Passengers Carried (pax/day): 6,356
Airports Served (-): 104



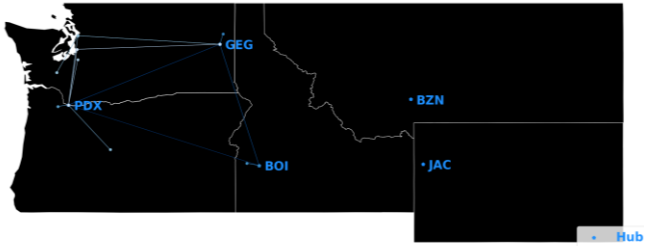
<u>19-seat</u>

Fleet Size (-): 72 (-61%)
Number of Flights (-): 305
Passengers Carried (pax/day): 3,540
Airports Served (-): 58



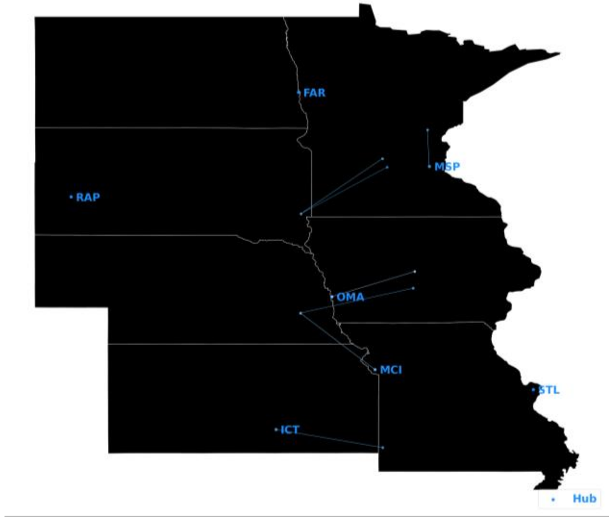
<u>30-seat</u>

Fleet Size (-): 12
Number of Flights (-): 51
Passengers Carried (pax/day): 1,329
Airports Served (-): 11



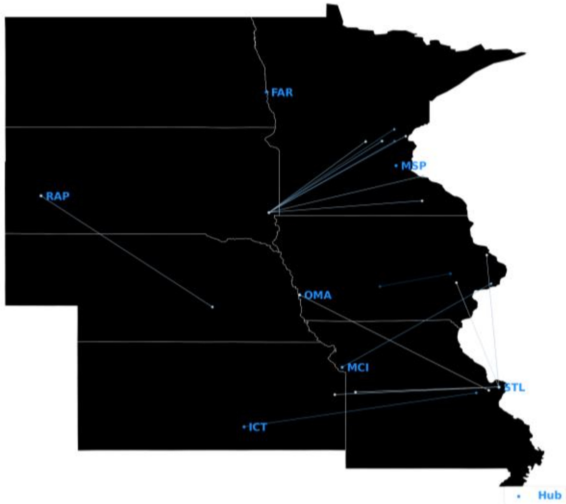
<u>9-Seat</u>

Fleet Size (-): 9
Number of Flights (-): 40
Passengers Carried (pax/day): 183
Airports Served (-): 12



<u>19-seat</u>

Fleet Size (-): 23 (-8%)
Number of Flights (-): 94
Passengers Carried (pax/day): 994
Airports Served (-): 23



<u>30-seat</u>

Fleet Size (-): 0
Number of Flights (-): 0
Passengers Carried (pax/day): 0
Airports Served (-): 0

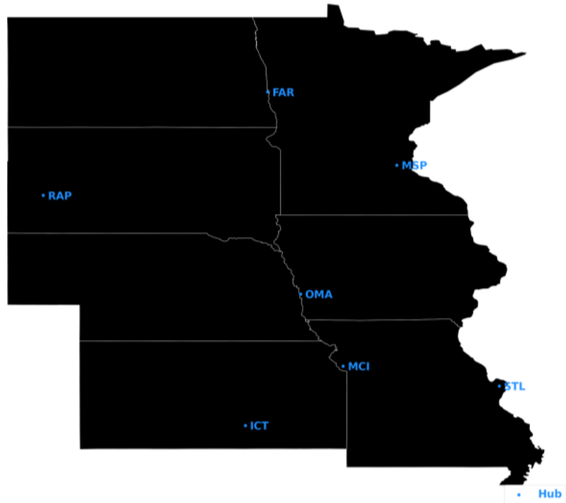


Table 22: Network of flights operated by the fleet of 9-seat, 19-seat, and 30-seat aircraft in the Midwest and Northeast Corridor for regional air mobility services

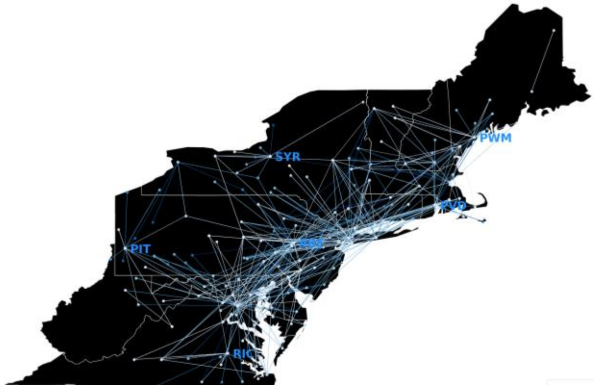
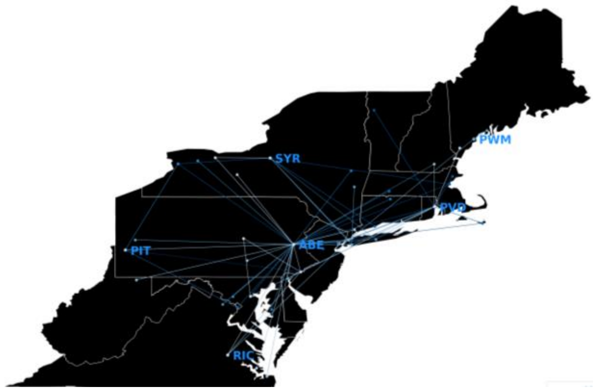
<table>
<tr>
<td><u>9-Seat</u>
Fleet Size (-): 637
Number of Flights (-): 1,918
Passengers Carried (pax/day): 13,675
Airports Served (-): 239
</td>
<td><u>19-seat</u>
Fleet Size (-): 269 (-53%)
Number of Flights (-): 790
Passengers Carried (pax/day): 10,155
Airports Served (-): 145
</td>
<td><u>30-seat</u>
Fleet Size (-): 50
Number of Flights (-): 231
Passengers Carried (pax/day): 6,349
Airports Served (-): 22
</td>
</tr>
<tr>
<td><u>9-Seat</u>
Fleet Size (-): 457
Number of Flights (-): 1,286
Passengers Carried (pax/day): 9,269
Airports Served (-): 154
</td>
<td><u>19-seat</u>
Fleet Size (-): 241 (-54%)
Number of Flights (-): 746
Passengers Carried (pax/day): 9,827
Airports Served (-): 112
</td>
<td><u>30-seat</u>
Fleet Size (-): 75
Number of Flights (-): 327
Passengers Carried (pax/day): 8,663
Airports Served (-): 41
</td>
</tr>
</table>

Table 23: Network of flights operated by the fleet of 9-seat, 19-seat, and 30-seat aircraft in the Southwest and Southern Great Plains for regional air mobility services

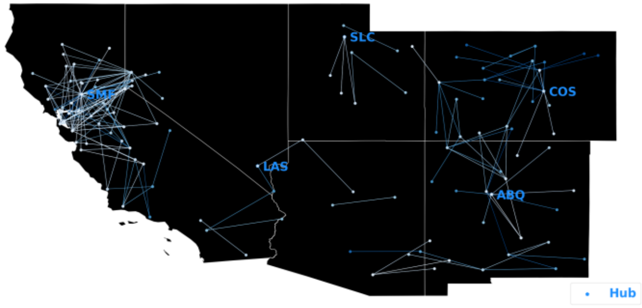
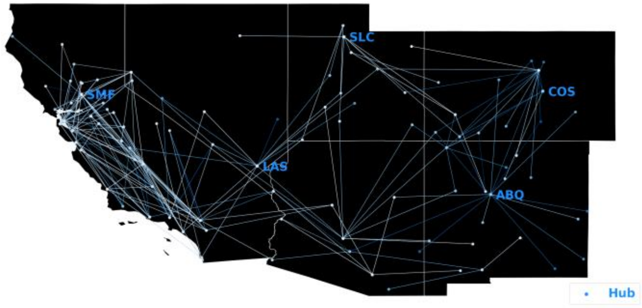
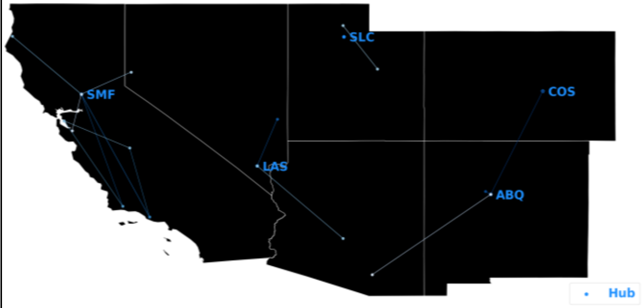
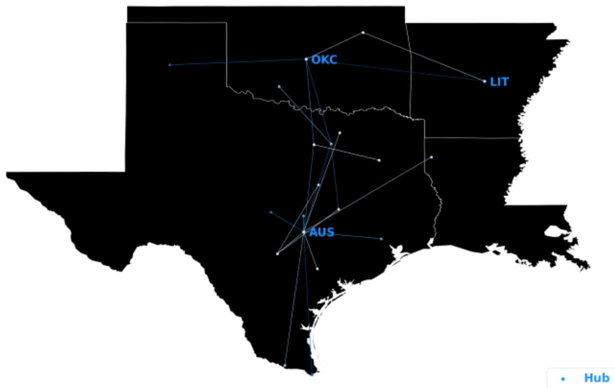
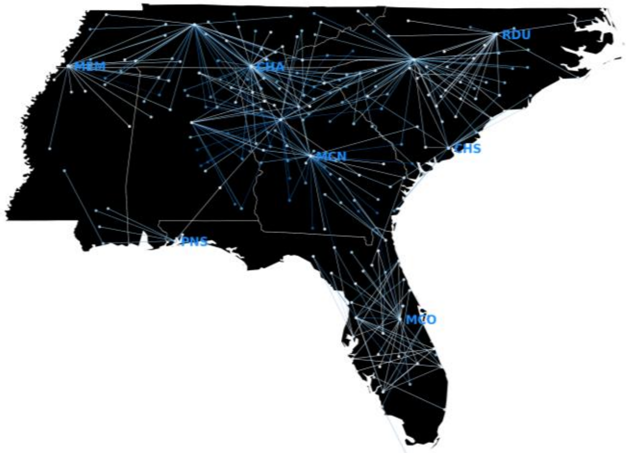
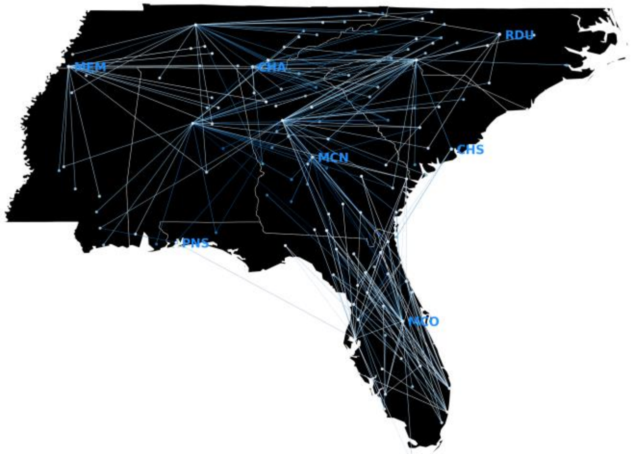
<u>9-Seat</u> Fleet Size (-): 282 Number of Flights (-): 818 Passengers Carried (pax/day): 6,163 Airports Served (-): 118  	<u>19-seat</u> Fleet Size (-): 212 (-70%) Number of Flights (-): 661 Passengers Carried (pax/day): 8,068 Airports Served (-): 101  	<u>30-seat</u> Fleet Size (-): 12 Number of Flights (-): 45 Passengers Carried (pax/day): 1,100 Airports Served (-): 17 
<u>9-Seat</u> Fleet Size (-): 374 Number of Flights (-): 1,125 Passengers Carried (pax/day): 8,160 Airports Served (-): 154  	<u>19-seat</u> Fleet Size (-): 405 (-35%) Number of Flights (-): 1,197 Passengers Carried (pax/day): 14,732 Airports Served (-): 163  	<u>30-seat</u> Fleet Size (-): 30 Number of Flights (-): 126 Passengers Carried (pax/day): 3,268 Airports Served (-): 20 

Table 24: Network of flights operated by the fleet of 9-seat, 19-seat, and 30-seat aircraft in the Southeast for regional air mobility services

9-Seat	19-seat	30-seat
Fleet Size (-): 433 Number of Flights (-): 1,402 Passengers Carried (pax/day): 9,937 Airports Served (-): 223	Fleet Size (-): 259 (-45%) Number of Flights (-): 819 Passengers Carried (pax/day): 9,951 Airports Served (-): 136	Fleet Size (-): 34 Number of Flights (-): 148 Passenger Carried (pax/day): 4,089 Airports Served (-): 22





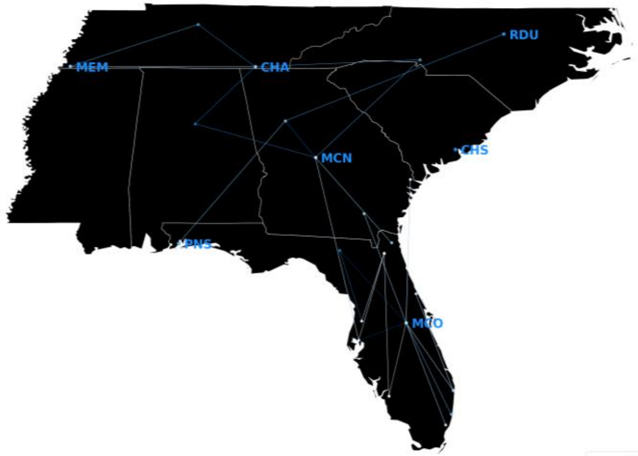


Table 25: Regional air mobility network & operations statistics using a fleet of 9-seat, 19-seat, and 30-seat aircraft

	Pacific Northwest	Northern Great Plains	Midwest	Northeast Corridor
Daily passengers carried (-):	9,255	1,177	24,177	20,059
Passenger carried fraction (-):	56%	26%	62%	59%
Nonstop passenger fraction (-):	79%	100%	75%	61%
Daily passenger-mile (pax.mi):	1,626,439	271,690	4,815,293	4,311,027
Daily flights number (-):	1,295	134	2,939	2,359
Load factor (-):	71%	55%	77%	78%
Airports served (-):	114	29	279	171
Airports served fraction (-):	80%	25%	81%	86%
Markets served (-):	565	46	1,281	1,270
Markets served fraction (-):	57%	14%	56%	54%
Avg. door-to-door time (hr):	2:23	2:04	2:12	2:50
Avg. travel time savings (-):	41%	53%	41%	39%
Optimization MIP Gap (-):	6%	6%	6%	8%

	Southwest	Southern Great Plains	Southeast
Daily passengers carried (-):	13,776	22,834	19,356
Passenger carried fraction (-):	57%	52%	55%
Nonstop passenger fraction (-):	88%	85%	76%
Daily passenger mile (pax.mi) / Daily passenger-mile (pax.mi):	2,725,332	4,818,557	4,100,406
Daily flights number (-):	1,524	2,448	2,369
Load factor (-):	70%	70%	72%
Airports served (-):	142	224	266
Airports served fraction (-):	81%	77%	73%
Markets served (-):	647	1,134	978
Markets served fraction (-):	43%	42%	49%
Avg. door-to-door time (hr):	2:23	2:21	2:21
Avg. travel time savings (-):	42%	40%	41%
Optimization MIP Gap (-):	6%	6%	6%

4. Conclusion

As part of this research, we have presented a framework to investigate the market for regional air mobility services, defined as markets with a demand between 10 and 75 passengers per day over distances between 100 and 350 miles. To the authors' knowledge, this is the first time that a regional air mobility market analysis is proposed at the county-to-county granularity and at a scale covering the entire United States.

We uncovered significant unmet demand for these regional air mobility services, and we have demonstrated that about half of this demand could be served profitably by regional air mobility operators provided that state-of-the-art regional aircraft with highly efficient powertrains are used. Focusing next on markets suitable for 19-seat aircraft (subset of regional air mobility markets with a demand capped at 50 passengers per day), we found that we could serve over 980 markets, which almost doubles the number of airports served in the United States by commercial scheduled operators. The fleet of aircraft required to fly these services is significant at over 2,700 units, but still in line with the number of aircraft operated by existing commuter operators in subparts of these regions (for instance Cape Air in New England operates a fleet of just under 100 aircraft across a much smaller part of the United States). When introducing additional aircraft gauges (9-seat and 30-seat aircraft), the market outlook for the 19-seat aircraft is not as bright. Indeed, for most routes that can be flown by both the 9-seat and the 19-seat, the 9-seat aircraft often manages to displace the larger aircraft.

In the future, we are planning to extend this research by integrating all seven mega-regions together to perform a single United States market-wide study. Doing so will help remove some of the biases introduced when adding arbitrary borders to the seven mega-regions.

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7. Copyright Statement

References

[1] Cook, G. N., and Goodwin, J., "Airline Networks: A Comparison of Hub-and-Spoke and Point-to-Point Systems," Journal of Aviation/Aerospace Education & Research, Vol. 17, No. 2, 2008. https://doi.org/10.15394/jaaer.2008.1443.

[2] Belobaba, P., Odoni, A. R., and Barnhart, C., The Global Airline Industry, Wiley, 2009. https://doi.org/10.4324/9781315630540.

[3] Wall, R., and Tangel, A., "I'm Flying In That? Unloved Turboprop Gets Second Look," The Wall Street Journal, 2019. URL https://www.wsj.com/articles/im-flying-in-that-unloved-turboprop-gets-second-look-11549277255, [Last accessed April 2nd, 2021].

[4] Morrow, D. J., "Twilight Of Turboprops?; Passengers Go Out of Their Way To Catch Jets," The New York Times, 2000. URL https: //www.nytimes.com/2000/02/18/business/twilight-of-turboprops-passengers-go-out-of-their-way-to-catch-jets.html, [Last accessed April 2nd, 2021].

[5] Justin, C. Y., Payan, A., Briceno, S., and Mavris, D. N., "Operational and Economic Feasibility of Electric Thin Haul Transportation," AIAA Aviation Forum, 17th AIAA Aviation Technology, Integration, and Operations Conference, 2017. https://doi.org/2514/6.2017-3283.

[6] Harish, A., Perron, C., Bavaro, D., Ahuja, J., Ozcan, M., Justin, C., Briceno, S., German, B., and Mavris, D. N., "Economics of Advanced Thin-Haul Concepts and Operations," AIAA Aviation Forum, 16th AIAA Aviation Technology, Integration, and Operations Conference, 2016. https://doi.org/10.2514/6.2016-3767

[7] Peterson, R., "Impacts of Airline Deregulation," Transportation Research Board, , No. 315, 2018.

[8] Thurber, M., "Surf Air Cuts San Carlos Noise with New Visual Approach," Jul. 2016. URL https://www.ainonline.com/aviationnews/business-aviation/2016-07-01/surf-air-cuts-san-carlos-noise-new-visual-approach.

[9] International Air Transport Association, "IATA reaffirms commitment to reducing emissions," , Oct. 2018. URL https: //airlines.iata.org/news/iata-reaffirms-commitment-to-reducing-emissions, [Last accessed April 2nd, 2021].

[10] U.S. Department of Transportation, Federal Aviation Administration, "National Plan of Integrated Airport Systems (NPIAS), 2021-2025 - Appendix A: List of NPIAS Airports with Activity and Development Estimate," Tech. rep., 2020.

[11] NASA, "Regional Air Mobility: Leveraging Our National Investments to Energize the American Travel Experience," Tech. rep., National Aeronautics and Space Administration, Apr. 2021.

[12] Holmes, B. J., Parker, R. A., Stanley, D., McHugh, P., Garrow, L., and John Olcott, P. M. M., "NASA Strategic Framework for On-Demand Air Mobility," Tech. rep., 2017.

[13] U.S. Department of Transportation, Federal Highway Administration, "Traveler Analysis, Framework, Exploring National Long Distance Passenger Travel Demand Modeling and Simulation," 2015. URL https://www.fhwa.dot.gov/policyinformation/ analysisframework/02.cfm, [Last accessed April 2nd, 2021].

[14] Justin, C. Y., Payan, A. P., and Mavris, D. N., "Integrated Fleet Assignment and Scheduling for Environmentally Friendly Electrified Regional Air Mobility," Transportation Research Part C: Emerging Technologies, 2022. https://doi.org/10.1016/j.trc.2022.103567

[15] McNally, M. G., The Four Step Model, 2nd ed., Pergamon, 2007, Chap. 3.

[16] Justin, C. Y., Payan, A. P., and Mavris, D. N., "Demand Modeling and Operations Optimization for Advanced Regional Air Mobility," AIAA Aviation Forum, Virtual, 2021. https://doi.org/10.2514/6.2021-3179

[17] Microsoft Bing, "Bing Map API," 2022. URL https://www.bingmapsportal.com/, [Last accessed June 2022].

[18] FlightAware, 2022. URL https://www.flightaware.com, [Last accessed June 2021].

[19] Internal Revenue Services, "Standard Mileage Rate," 2021. URL https://www.irs.gov/tax-professionals/standard-mileage-rates, [Last accessed May 22nd, 2021].

[20] Bureau of Transportation Statistics, "Origin and Destination Survey Data," Apr. 2021. URL https://www.bts.gov/topics/airlinesand-airports/origin-and-destination-survey-data, [Last accessed April 2nd, 2021].

[21] Roy, S., Herniczek, M. T. K., German, B. J., and Garrow, L. A., "User Base Estimation Methodology for a Business Airport Shuttle Air Taxi Service," Journal of Air Transportation, Vol. 29, No. 2, 2021, pp. 69–79.

[22] U.S. Department of Transportation, Office of the Secretary of Transportation, "The Value of Travel Time Savings: Departmental Guidance for Conducting Economic Evaluations Revision 2 (2016 Update)," Tech. rep., 2016.

[23] McFadden, D., Conditional Logit Analysis of Qualitative Choice Behavior, Frontiers in Econometrics (New York: Academic Press), 1973, Chap. 4, pp. 105–142

[24] U.S. Department of Transportation, "Essential Air Service," 2017. URL https://www.transportation.gov/policy/aviationpolicy/small-community-rural-air-service/essential-air-service, [Last accessed April 2nd, 2021].

[25] Federal Aviation Administration, "Air Traffic by the Number", 2022, URL https://www.faa.gov/sites/faa.gov/files/air_traffic/by_the_numbers/Air_Traffic_by_the_Numbers_2022.pdf, [Last accessed July 15th, 2022].

[26] Cai, Y., Pastra, C., Monjon, M., Thind, J., Gladin, J., Mavris, D., "System-level Trade Study of Hybrid Parallel Propulsion Architectures on Future Regional and Thin Haul Turboprop Aircraft", AIAA Scitech, 2023.

[27] Morejón Ramírez, L., Decroix, J., Justin, C.Y., Payan A. P., and Mavris, D.N., "Design and Operation Considerations for the Integration of Fleets of Regional Air Mobility Aircraft at Large Hubs", AIAA Aviation Forum, Virtual, 2021, https://doi.org/10.2514/6.2021-3178