Impact of Electric Aviation on the CA Air Travel Network

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1 Introduction

Most airline networks today utilize a hub and spoke routing system. While this structure has advantages, such as well-timed connecting flights and relatively inexpensive network growth [1], it can be costly for passengers who simply need to pass through the hub, as shorter flight segments are more costly per mile [2]. In addition, it can be inefficient compared to a point-to-point airline network.

Hub to hub routes (i.e., SFO to LAX) are flown dozens of times a day with much higher passenger volume, while hub to smaller, regional airport routes are flown once or twice a day, with lower passenger loads, resulting in higher CO_2 emissions released per passenger. In addition, the high amount of energy consumption required during takeoff and climb out for a shorter flight results in higher emissions per mile than that of a long-haul flight [3], [4]. Taking alternative transport modes, for instance cars (internal combustion), the Amtrak, or buses, however, are not as time-efficient, and may not result in significant emission reductions.

The current development and in some cases, manufacture and sale of electric aircraft, from companies such as Eviation, ZeroAvia, Airbus, and Wright Electric, has called into question the role of electric aircraft in not only decarbonizing the aviation industry, but also in shifting the hub and spoke structure of airline networks toward a point-to-point system. Baumeister et al., 2020 explores the potential greenhouse gas (GHG) emission reductions of replacing jet fuel aircraft on short-haul flights, train, and private vehicle trips with electric aircraft in Finland, taking into account CO_2 emission reductions and door-to-door travel times [5]. The authors found that electric aircraft in Finland could be recommended for replacing jet fuel aircraft on short-haul flights, but were only advantageous in terms of travel times and emissions for longer routes (greater than 170 km) compared to ground travel. In this study, we also estimate the potential CO_2 reductions and travel times of switching from ground travel to electric air travel in California. Baumeister et al., however, did not consider the potential costs of the electric aircraft ticket versus the train ticket versus fuel costs for private vehicles, an aspect we address in this project.

This study aims to (1) estimate the amount of emissions arising from ground commuting in California between 2011 to 2015, (2) identify the commuting routes that will benefit from electric aircraft, comparing ground and air CO_2 emissions, door-to-door travel times, and fuel versus ticket costs, and (3) evaluate how the existing California air travel network structure changes after adding new electric aircraft links.

Furthermore, there are two network structures we focus on in this study: small-world and scale-free. Small world networks are well-connected, having higher average clustering coefficients and shorter path lengths than random networks [6]. Scale-free networks contain hubs, large nodes with whom new links prefer making connections, and its degree distribution follows a power law [7]. In this study, we examine how the addition of new electric aircraft routes to the current California aviation network allows smaller, less-frequented regional airports to play an important role in air travel, potentially shifting the network away from a hub and spoke model.

2 Methods and Data

2.1 Ground and Air Travel Networks

We used ground commuting flows in California from 2011 to 2015, provided by the American Community Survey [8], and the Federal Aviation Administration's (FAA) Aviation System Performance Metrics (ASPM) database [9]. We constructed ground and air travel networks from these two databases and used networkx in Python to calculate network metrics such as betweenness centrality, clustering coefficient, and average shortest path length.

In addition, in order to accurately estimate electric air travel times, CO_2 emissions, and ticket prices, we based the battery mileage, passenger capacity, and hourly operating costs off of an electric aircraft currently in development: the Alice, from Eviation [10].

2.2 Emission Calculations

We multiplied an emission factor for internal combustion vehicles of 0.231, in units of per passenger-mile, to the ground commuting flows to find the total car emissions [11].

The CO_2 emissions (E_r) of electric aircraft trips were calculated with the following equation:

$$E_r = \eta f_r (EF_A) d_r \tag{1}$$

In Equation 1, η refers to the energy consumption per mile (kWh per mile), f_r denotes the number of flights the chosen aircraft needs to make up one jet fuel flight for route r, EF_A refers to the emission factor of charging the aircraft at airport *A* (kg CO_2e per kWh) and d_r refers to the distance (miles) of route *r*. Emission factors were calculated with a weighted average of an airport's electricity power mix and energy source emission factors detailed by a report from the Intergovernmental Panel on Climate Change [12].

2.3 Door-to-Door Travel Times

County centroids were used as the origins and destinations for ground commuting trips. Private vehicle trips consist of one segment (centroid to centroid), while air travel trips consist of three segments: origin county centroid to origin airport, origin airport to destination airport, and destination airport to destination county airport.

We used Bing's Distance Matrix API [13] to estimate the travel times for ground commuting trips, as well as the ground segments of the aircraft trips. To estimate air travel time, we divided the distance for each route by the maximum cruising speed of the Alice.

2.4 *Fuel Costs versus Airplane Ticket Prices*

In order to calculate the fuel cost for each ground trip, we multiplied the mileage of the car used by the distance of the trip and the gas price, in USD per gallon. Because the ACS data contained no information about the models of the car used for these trips, we used the mileage of a midsize sedan (24 mph). In addition, we used a high and low estimate for fuel costs of 3.67 USD per gallon (2019) and 4.6 USD per gallon (November 2021) [14].

For passengers, airplane ticket prices are largely comprised of two parts: hourly operating costs and taxes. The operating cost includes the cost of fuel (in this case, charging), crew, landing fees, and maintenance [15], while the taxes include a federal 7.5% tax, segment and security tax, and passenger facility charge [16]. The hourly operating cost of the selected aircraft has been estimated to run from 250 to 350 USD per hour [17]; we used the higher value for our calculations. This operating cost was scaled by the travel time for each route and divided by the number of passengers to obtain a per-passenger ticket cost. After adding individual passenger taxes to the scaled operating cost and adding a 10% profit margin for the airlines, we obtained an electric aircraft flight cost.

3 Results

3.1 *Original Air Travel Network Characteristics*

Network metrics were calculated for the existing air transportation network created from the ASPM data for later comparison against the network with electric aircraft links.

	Original Air Network	Small World *(p = 0.134)*	Scale Free *(m = 11)*
Num. Nodes	43	43	43
Num. Edges	247	215	352
Average degree	11	10	16
Clustering Coefficient	0.433	0.483	0.47
Avg. Shortest Path Length	1.894	2.02	1.611

Table 1. Network properties for the original air transportation network.

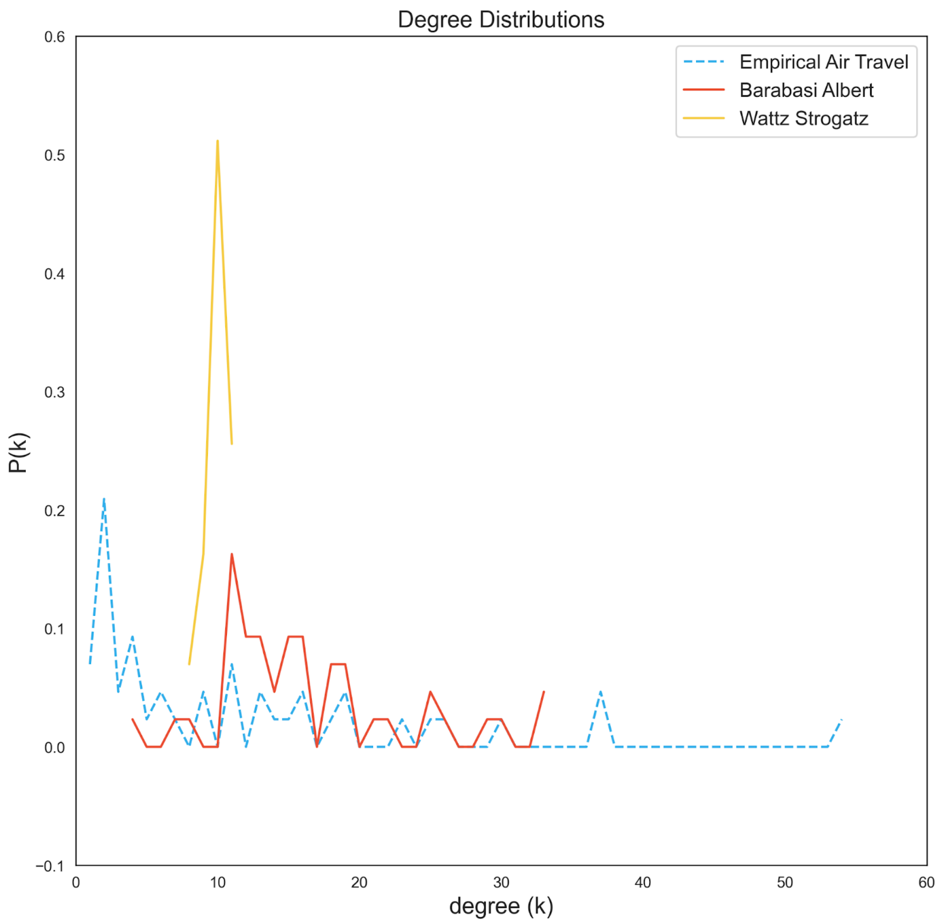

Fig 1a. Degree distribution of the CA regional air network compared to the degree distributions of the fitted scale-free (Barabasi Albert) and small-world (Wattz Strogatz)

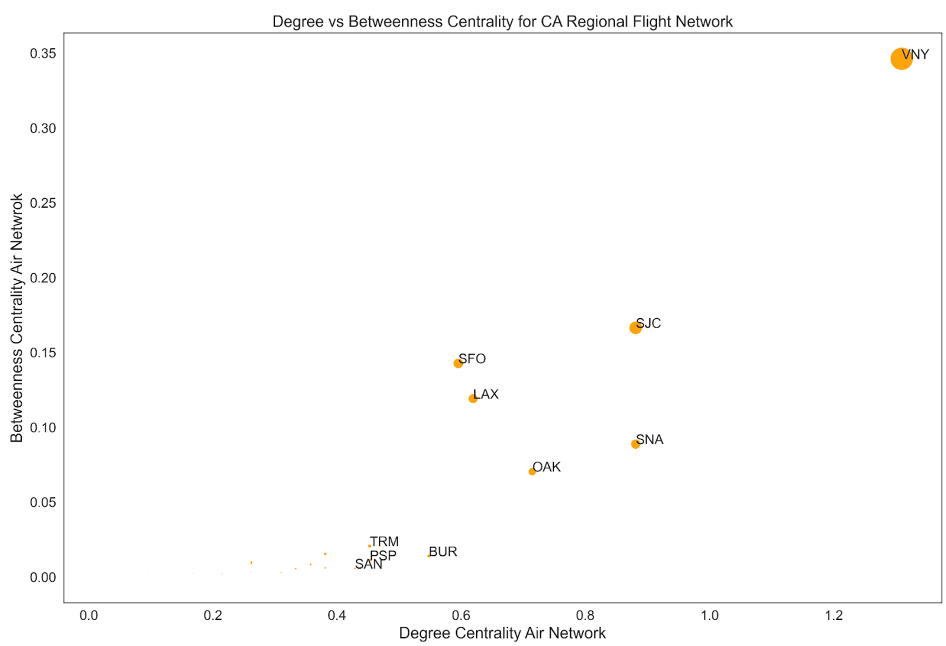

Fig 1b. Degree versus betweenness centrality for the air travel network

We calculated average degree, average clustering coefficient, and average shortest path length for the original network, finding that our network properties had similarities with both the small world and scale free models. (Table 1). However, the degree distribution of our empirical network follows more closely that of a scale free network (Fig 1b), indicating that nodes of higher degree (i.e., hubs) are much more uncommon (probability < 10^{-2}) than nodes with lower degrees. Lastly, Fig 1b shows that nodes with higher degrees (VNY, SFO, LAX and SJC) also have high betweenness. In other words, airports that have many links are also serve as the bridges connecting wholly separate airport communities, a feature characteristic of the hub-and-spoke structure of airlines.

3.2 Network Emissions and Impact of Mode Shifts

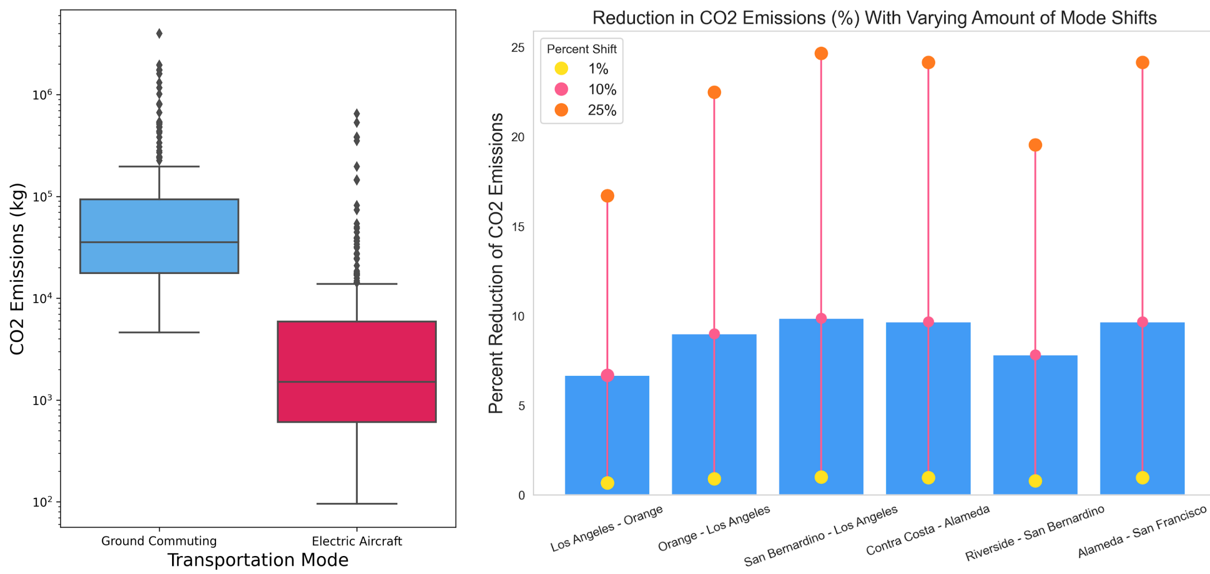

Fig 2a. CO_2 emissions for ground versus air commuting. **Fig 2b.** Percent reduction of CO_2 emissions for the top 6 commuting flow routes with different percentages of mode shifts (1, 10, and 25%)

3.3 Door-to-Door Travel Times

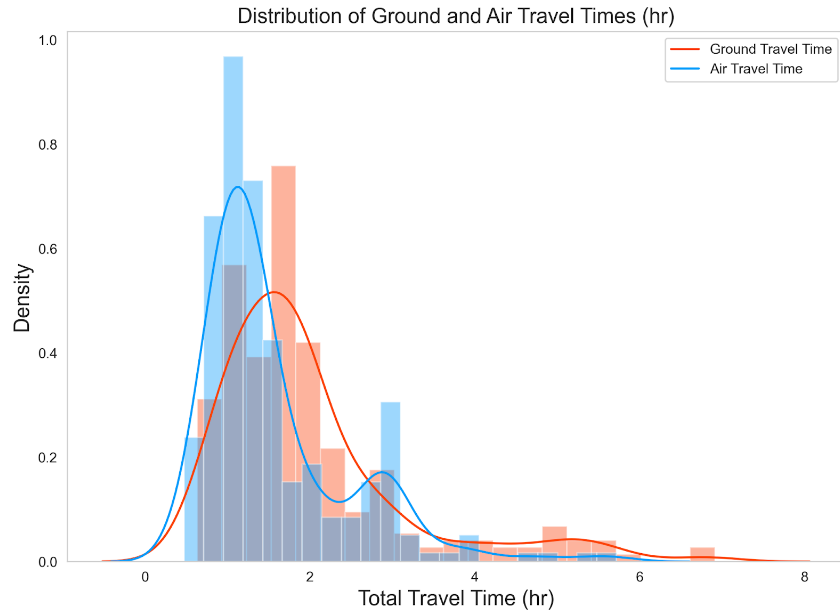

Fig 3. Comparison of door-to-door travel times of ground travel versus air travel.

While electric aircraft are faster than cars for the majority of routes, there are several routes for which cars are actually faster. This may be because for shorter routes, for instance Los Angeles County to Orange County, a passenger would need to drive to and from the airport as well as fly from one airport to the other. For routes like these, driving is a much more time-efficient option.

3.4 Fuel Costs versus Airplane Ticket Price

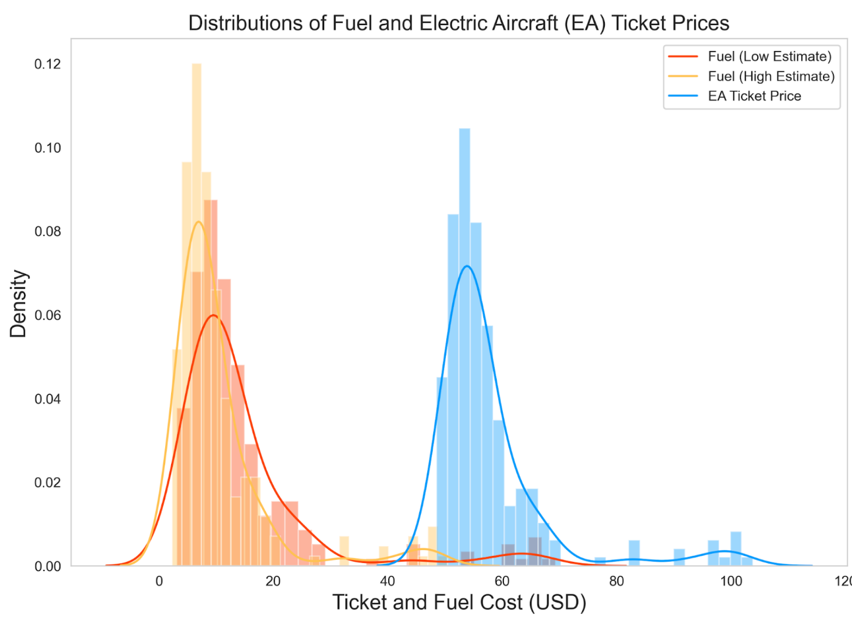

Fig 4. Price comparison for routes between electric aircraft tickets, an expensive fuel estimate, and a cheaper fuel estimate

3.5 *Tradeoffs and Route Selection Criteria*

While electric aircraft tickets are generally more expensive than fuel costs, the travel time saved may be worth the extra cost. Likewise, a certain amount of CO_2 emissions reduction may be worth a more expensive electric aircraft ticket. We calculated the difference in travel times per hour saved and the difference in ticket price per kilogram of CO_2 reduced. On average, it costs passengers 121 USD to save one hour of travel with the electric aircraft and 7.3 USD to reduce emissions by 1 kilogram CO_2. Therefore, routes for the new electric aircraft network were selected based on the criteria: (1) the route is feasible for the electric aircraft (i.e., within range, frequently driven), (2) the time-cost tradeoff value is less than the mean (121 USD per hour), (3) emission-cost tradeoff value is equal to or less than the cost of carbon capture and sequestions, 0.06 USD per kilogram CO2 [18]. Using this criteria, 73 routes of the original 247 ground commuting routes in California were selected.

3.7 New Electric Aircraft Network Characteristics

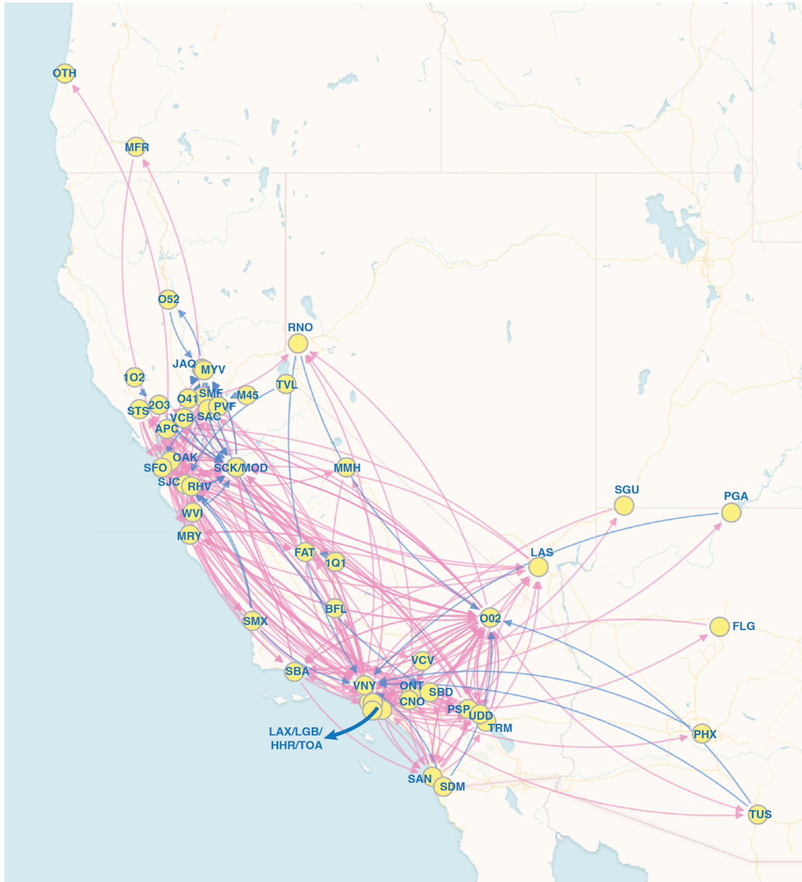

Fig 5. New CA air travel network with electric aircraft links. Existing routes are in pink, electric aircraft routes are in blue.

	New Air Network	Small World *(p = 0.124)*	Scale Free *(m = 9)*
Num. Nodes	70	70	70
Num. Edges	190	140	325
Average degree	5	4	9
Clustering Coefficient	0.336	0.343	0.218
Avg. Shortest Path Length	3.059	4.05	2.085

Table 2. Network properties for the new air transportation network

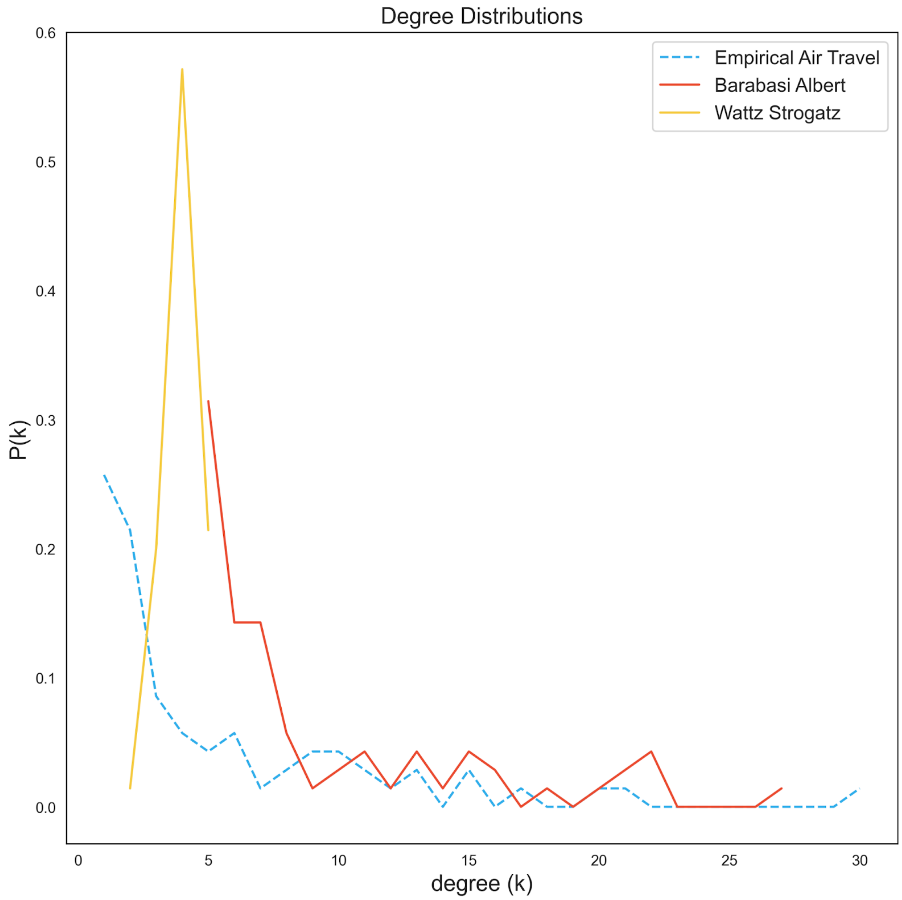

Fig 6a. Degree distribution of the new CA electric aircraft network compared to fitted small world and scale free models.

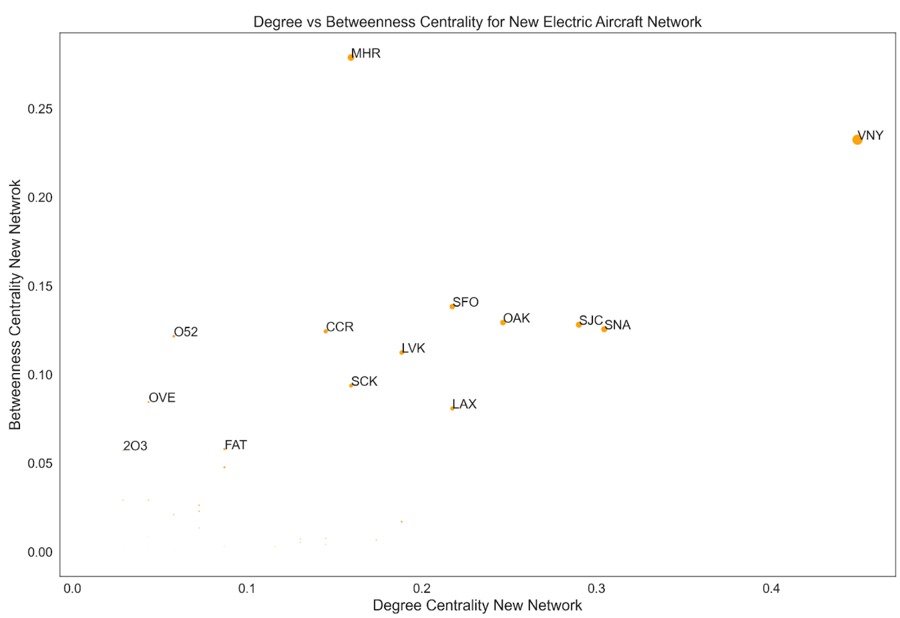

Fig 6b. Degree versus betweenness centrality for the new, electric aircraft network

The results in Table 2 suggest that the new empirical network has shifted toward a small world structure, as the number of edges, average degree, and average clustering coefficient are closer to the small world than the scale free network. Fig 5a, however, shows that the degree distribution still resembles that of a scale free network; the majority of airports have low degrees, and only a select few have high degrees.

4 Discussion and Conclusions

The new air travel network with added electric aircraft links still shares network properties with scale free and small world networks. The average degree, average shortest path length, and clustering coefficient are similar for all three models. In addition, the degree distribution of both the original and new air travel network follows the degree distribution of a scale free network. Despite this, Fig 5b shows that — in direct contrast to Fig 1b — airports with high degree in the new network do not necessarily have high betweenness, and vice versa. Very small, regional airports such as 2O3, OVE, and O52 have low degree centrality, but high betweenness, indicating that given the opportunity, these airports are important bridges, establishing direct routes that would have otherwise had to have gone through a hub. We conclude that the addition of electric air commuting links to California's aviation network — based on a multifaceted set of criteria — shifts the aviation network away from hub and spoke, and toward point-to-point.

5 Future Work

The greatest source of uncertainty lies within the ground commuting data. This data includes origin counties, destination counties, and flows between the origin-destination pairs, but no data about the type of cars (i.e., internal combustion engines, electric, hybrid-electric). This study would benefit from more detailed ground commuting datasets so that emissions can be more accurately estimated.

Furthermore, while this study focuses on three criteria (CO_2, ticket prices, and travel times) for adding new routes, there are other factors that should be accounted for when selecting routes for electric aircraft use. For instance, there are complex scheduling and logistical decisions, including airport runway capacities and air traffic management, that must be made when adding new routes to an airline network. There is also passenger demand to take into consideration. In addition, we focused solely on the Alice from Eviation when calculating emission reductions, travel times, and ticket prices, as the Alice is currently closest to commercialization. Future work on this topic would benefit from considering the aircraft characteristics of other up-and-coming electric aircraft.

Lastly, we based our new, electric aircraft links off of only gound commuting (i.e., private vehicle). Further studies on this topic should, as Baumeister et al. did, also take into account other transportation modes, such as high speed rail and bus.

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