THE IMPACT OF THE LONG-RANGE TWIN-ENGINE JET ON THE AVIATION INDUSTRY

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This paper studies the impact of the long-range twin-engine aircraft on international aviation. Specifically, we study whether the introduction of smaller aircraft capable of long-range service has unlocked routing options that would not have been economically feasible before the new technology was available. A probit model is estimated to ascertain whether increased availability of twin-engine aircraft leads to increased probability that a city-pair is served by a direct flight. Both the model and various descriptive statistics indicate that markets with less desirable characteristics become more likely to receive direct flight service as twin-engine aircraft gain market share.

I. Introduction

Throughout the era of commercial aviation, there has existed a general correlation between an aircraft's size and the length of the flight segments that it flies. Large aircraft have typically carried passengers on longer flights between major cities, while smaller aircraft have transported passengers on the shorter trip from a major city to their final destinations. This routing method came to be known as the "Hub-and-Spoke" system, meaning that many flights originate from a small group of major airports known as hubs

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while all other airports in the network only offer flights to and from the hubs. This system works to the advantage of the airline because passenger concentration in the hubs allows for the airline to have a large number of passengers to fill its long flights, which are served by larger planes. Additionally, this system allows for an airline to leverage economies of scale in terms of systems and personnel in place at hub airports.

However, the Hub-and-Spoke routing system's rise to the industry standard can also be partially attributed to technological constraints. Historically, only the largest aircraft in an airline's fleet have been suited to fly long routes due to the general correlation between aircraft size and service range. Therefore, a Hub-and-Spoke routing model was necessary because only large aircraft were able to serve long distance flights and so airlines needed a large number of passengers demanding a long-haul flight in order to operate profitably. Airlines solved this high demand threshold problem by concentrating passengers in hub airports so that the passengers with different points of origination and different final destinations would fly the long-haul portion on the same aircraft.

This historical technological constraint raises the question as to whether airlines would still use the Hub-and-Spoke system if they did not need to use their largest aircraft to fly their longest flight segments. It is possible that airlines would still favor the Hub-and-Spoke model in order to leverage economies of scale at hub airports and limit the overall number of segments flown for simplicity, but perhaps they would instead choose to fly passengers more directly to their destinations using smaller aircraft. This method of direct connection across many or all airports in a network, known as a "Point-to-Point" model, has not to date been used by a major international airline. However, it is not clear whether this is due to the true organizational efficiency of the Hub-and-Spoke system or the lasting legacy of former constraints.

Airlines have been presented an opportunity to depart from the Hub-and-Spoke model in recent years due to technological advances that could pave the way for new routing possibilities. New twin-engine aircraft that have smaller seating capacity than, yet similar service range to, traditional four-engine long-haul aircraft have come to market. In particular, the Boeing 777, Boeing 787, Airbus A330, and Airbus A350 offer substantially smaller cabins than four-engine alternatives while also retaining the long-haul service range required to operate long flights that have traditionally been served by four-engine aircraft. This technological advancement (Table 1) is due both to the far more efficient engines and the relaxed regulatory environment[1] that has come as jet engines have become more reliable and seen far fewer in-flight failures. The innovation has given airlines an opportunity to operate long-haul flights with fewer demanding passengers, potentially introducing more direct routing options that would not have been economically viable in the past.

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[1] Until at least the early 1990s, Extended-range Twin-engine Operational Performance Standards (ETOPS) prevented twin-engine aircraft models to fly further than a set distance away from a diversion airport for fear of engine failure requiring an emergency landing. As twin-engine aircraft were introduced with increasingly reliable engines and could fly further after the failure of one engine, these regulations have been relaxed, allowing twin-engine transoceanic flights formerly unviable for regulatory reasons to be flown by newer aircraft models.

Aircraft	Passenger Seating	Range (nm)	Engines
Airbus A380	575	8,000	4
Boeing 747-8	410	8,000	4
Airbus A350-900	325	8,100	2
Boeing 777-200LR	317	8,555	2
Boeing 787-9	290	7,635	2
Airbus A330-900neo	287	7,200	2
Airbus A330-800neo	257	8,150	2
Boeing 787-8	242	7,355	2

Table 1: Passenger Capacity and Service Range of Current Long-Range Aircraft

The introduction of twin-engine long-haul aircraft is one that would theoretically benefit both the airline and the passenger in both a Hub-and-Spoke model and a Point-to-Point model. In the case of a Hub-and-Spoke model, the replacement of larger, four-engine aircraft with smaller twin-engine ones would allow for higher flight frequency along the same routes for a given number of passengers. This would bring an increase in flight options for a passenger flying any given route and may allow air travel to better suit a passenger's time preferences. For an airline, a smaller aircraft would allow for both improved fuel efficiency and a smaller cabin that could allow the airline to more closely match flight supply to customer demand and fly with higher load factors, a larger percentage of available seats filled. Additionally, it has been shown that airlines can charge higher ticket prices for higher flight frequency due to improved passenger convenience (Brueckner 2004), allowing them to earn more revenue in exchange for passenger time savings.

In a Point-to-Point model, the new aircraft benefit the passenger because they may allow for flights between cities that could not have been directly connected by larger aircraft. This opportunity to introduce direct flights when a connection may have formerly been required dramatically reduces travel time for passengers traveling along those routes, eliminating both layovers and redundant travel between airports that are not directly en route to the final destination. The airline will see similar benefits in this case as the increase in direct flights means that the airline will carry passengers fewer miles than before, saving costs on fuel and fees paid to connecting airports. Additionally, passengers have a higher willingness to pay for direct flights due to increased convenience and time savings, meaning that the establishment of more direct routing could create revenue growth (Fageda and Flores-Fillol 2012).

II. Literature Review

This paper draws from an analysis of the impact of the regional jet's use after its introduction in the early 1990s (Brueckner and Pai 2009). The regional jet, while only used on shorter domestic flights, was a similar technological innovation to the twin-engine long-range jet in the sense that it offered a smaller cabin size than other aircraft with similar service ranges, yet had a much longer range than preexisting turboprop aircraft of its size. Brueckner and Pai created a theoretical mathematical framework that predicted that the introduction of the regional jet would lead to an increase in Point-to-Point routing for United States domestic flights.

The routes that would be theoretically affected, termed "thin" routes, were described as routes where direct service was not profitable for the airline using previous technology. This change in economic viability was due to the fact that demand for direct air travel on thin routes was small enough that an airline could not profitably fly a larger jet along the route while smaller aircraft did not have the service range to connect the two cities. Brueckner and Pai predicted that thin routes would connect cities with smaller populations, low proportions of wealthy residents, and distance separation that could not be addressed by turboprop service.

Empirically, however, Brueckner and Pai found limited change in airline routing models as a result of the introduction of regional jets. Rather, it was found that regional jets served two distinct purposes in the market: increasing service frequency on segments that were already flown by larger jets and replacing segments that were formerly flown by turboprop aircraft. Therefore, the theoretical hypothesis that regional jets would lead to a shift toward Point-to-Point service along thin routes was not correct over the relevant data period.

It has been shown that a monopolistic air carrier serving a given number of cities should, in theory, choose either a Hub-and-Spoke system with one single Hub or a pure Point-to-Point system with no hub (Hendricks, Piccione, and Tan 1995). This result holds under the assumption that economies of density exist, as they do in the world of commercial aviation. This could mean that the failure to move toward a more mixed routing model after the introduction of the regional jet was attributable to the inefficiency in the intermediate term resulting from a transition of routing models.

Prior to the introduction of long-haul twin-engine aircraft, flight data indicated that there was a correlation between distance between airports and aircraft size (Pai 2010). In addition, this longer distance typically led to a decrease in flight frequency. Both of these impacts may be counteracted by the technological shock, as the options to provide higher frequency and smaller aircraft on long-distance routes have dramatically increased in the past decade.

More broadly in the literature, analysis indicates that there exists a general preference for smaller aircraft over larger ones in airline fleet construction. The increase over time in demand for air travel has been met not by larger average aircraft size but rather by higher flight frequency (Givoni and Rietveld 2009). This may represent a preference for small aircraft over larger ones when the option is available, underscoring the motivation of this paper for the case in which a smaller option has only recently become available.

There is some research that investigates whether the "Low Cost Carrier" airline model, in which an airline cuts out some traditional services of air carriers in order to offer lower prices, can be adapted to long-haul routes. It has been speculated that because superfluous services and expenses are a relatively smaller portion of the cost of a long-haul flight, it may be more challenging for a low cost model to be applied in the space[2] (Francis et. al 2007). Domestic and short-haul Low Cost Carriers have traditionally subscribed more to the Point-to-Point model than to Hub-and-Spoke, so this insight may be a blow to the feasibility of extensive international Point-to-Point networks.

In the realm of "thin" routes and mechanisms to serve them on shorter flights, the United States and Europe have seen different models used to reach these thin routes (Fageda and Flores-Fillol 2012). The United States has served thin routes with regional airlines, offering more frequent yet also more expensive flights. The EU, on the other hand, has served them with Low Cost Carriers, which offer lower flight frequency but also lower fares. The differences in the ways in which thin routes have been served

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[2] This theory is supported by recent financial struggles of long-haul Low Cost Carriers, most visibly Wow Air. Wow attempted to serve low cost long haul flights out of a hub in Reykjavik, Iceland but was forced to cease its operations in March 2019 due to financial struggles.

historically raises the question of which mechanism, or what combination of the two mechanisms, could be effective for the international equivalent of these thin routes.

Additionally, there is a distinct connection between business traveler preferences and Point-to-Point routing. Business travelers have a higher value for time lost in air travel, and for that reason have higher willingness to pay for direct service that reduces total travel time (Fageda and Flores-Fillol 2012). This may create particularly strong incentives for long-haul direct flights connecting international business centers, as airlines may be able to command substantially higher prices by serving business travelers more efficiently. For this reason, it is likely that four-engine aircraft already provide nonstop service between international business centers, meaning that twin-engine nonstop service on these routes will likely not represent new service altogether. Rather, in accordance with the thin routes hypothesis, the new routes established by the A330, A350, 777, and 787 may be between cities with a relatively lower proportion of business travelers who will pay higher fares for greater travel convenience. Along these routes, the possibility arises that four-engine aircraft were too large to offer service but new twin-engine aircraft can profitably meet demand.

Another cost consideration for long-haul flights is the inefficiency of fuel use over increasingly long routes. Because longer flights require that an aircraft carry more fuel, aircraft become less fuel efficient over longer distances. However, takeoff and ascent are also very fuel inefficient, so each aircraft model has a breakeven point after which it becomes more efficient to land and refuel than to carry enough fuel for a direct flight (Filippone 2012). For example, this cutoff mileage for the Boeing 777-300 is about 3,000 nautical miles (see Figure 1). This introduces an additional variable for long-haul flights, as sufficiently long flights become less efficient in pure fuel economy terms than flights that stop at a central point, regardless of the service range of the aircraft. This means that an airline looking to capture the high willingness to pay of customers looking for nonstop service must balance higher fares they can command with the costs affiliated with offering such service.

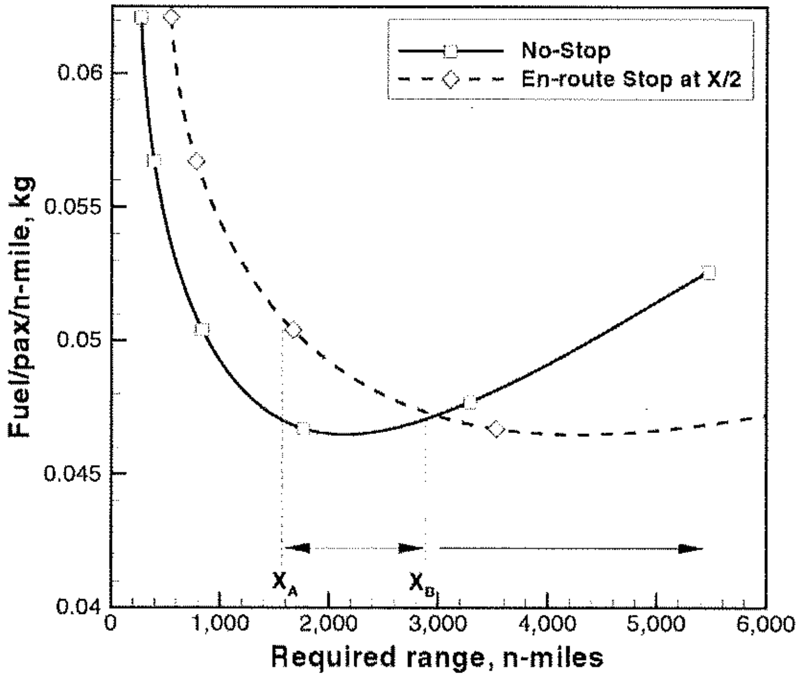

Figure 1: Fuel Efficiency of 777-300 by Flight Distance

Finally, analysis from before the commercial release of the Airbus A380 and Boeing 787 concluded that despite similar service ranges and per-seat mile costs, the A380, a large four-engine aircraft, had a substantially more severe risk profile (King 2007). This is due to the higher passenger threshold required for a profitable A380 route as well as the fact that use of the A380 requires larger crews and support networks both onboard and on the ground at airports. This less severe risk profile may be the reason for the historical use of smaller aircraft on segments that are newly introduced (Pai 2006). This may encourage the introduction of new long-range international flights using twin-engine long-range aircraft, given that new aircraft will be the smallest ever capable of serving these segments.

III. Motivation

We notice that in the past 15 years, the number of direct, long-range international flight segments served has grown at a faster rate than the number of international passengers traveling to and from the United States (Table 2). It is intuitive that the number of segments in service would grow with an increase in passengers, but less clear why its growth rate would exceed that of passengers served. We wonder whether this departure of two metrics that would intuitively move in lockstep could support the effect of technology that Brueckner and Pai suggested in a different context. If this were the case, it would shed light on the future of the aviation industry, as outstanding airline orders indicate that twin-engine jets will continue to take a larger share of the overall long-range commercial aviation fleet worldwide.

Year	Passengers (millions)	Segments Flown
2003	64.2	139
2004	73.9	145
2005	81.4	150
2006	86.4	161
2007	90.5	178
2008	91.6	188
2009	85.8	189
2010	91	185
2011	92.5	197
2012	94.4	201
2013	97.5	202
2014	99.9	216
2015	102.2	229
2016	104	241
2017	107.7	267

Table 2: International Passengers and Segments Flown, 2003-2017

We have reason to suspect that the introduction of long-range twin-engine jets may have the impact that Brueckner and Pai expected to see, but did not find, in regional jet implementation. First, the benefits to airlines of introducing flights on new, thinner segments are far greater in magnitude for long-haul flights. The savings to an airline from flying more directly are much larger for a long-haul international route due to the time and resource drains of a Hub-and-Spoke model. On such a large scale, the number and cost of redundant miles traveled is much more intense on long-haul routes than it is on shorter, domestic ones. This may motivate the airlines to more quickly make adjustments to their route networks or otherwise more carefully consider the possibility of adding new direct segments. Additionally, more direct routing on long flights will increase the time savings to passengers of direct flights. Therefore, Fageda and Flores-Fillol's observation that passengers are willing to pay more for direct flights may increase over longer distances as their time savings become more substantial.

Additionally, there are infrastructure considerations that were not considered by Brueckner and Pai that may influence our results. In particular, in analysis of domestic routing it must be considered that many airports in domestic route networks are very small and may be unable to accommodate the increased traffic flow brought on by a move closer to Point-to-Point route networking. In contrast, the airports that are connected by long-haul international flights are by comparison much larger and, while still sometimes constrained in size, more likely than regional airports to be capable of accommodating an increase in daily flights. This may reduce the frictions and structural barriers to changing route networks that may have hindered airlines from using regional jets in the manner that Brueckner and Pai predicted.

We can see anecdotally that the new aircraft seem to be used to connect cities that are not traditionally considered aviation hubs. For example, China Southern Airlines operates daily flights with its new Boeing 787 aircraft direct from its main hub in Guangzhou to a variety of American cities. More interestingly, however, it also recently began to offer a daily flight from the Chinese city of Wuhan to San Francisco. This can also be seen in the Western Hemisphere, as British Airways is using its 787s to fly directly from London to cities such as Austin and San Jose, among others. These new segments stand in contrast with the formerly strict Hub-and-Spoke model, where a passenger may have had to fly from Wuhan to Guangzhou to Los Angeles to San Francisco or from London to Dallas to Austin. We wonder whether this flight would be feasible if flown by a 410-seat Boeing 747 rather than the 242-seat Boeing 787 or if it is only made possible by the new long-range aircraft. Additionally, if new segment service is becoming possible with new technology, this may indicate that more direct routing will become more prevalent in the coming years as frictional problems with introducing new segments subside.

What is less clear, however, is whether this trend is borne out across all data and, if so, whether or not it is causal. There has been a substantial increase in air travel over the past two decades, meaning that naturally new segments will be introduced and utilized as the number of passengers needing transport rises. Therefore, this paper seeks to ascertain whether technology has caused more direct routing or whether the new segments were simply introduced as demand for air travel increased.

We can clearly see a shift in industry preference toward the smaller, twin-engine aircraft in the form of current orders for new aircraft, most notably shown by Airbus's February 2019 decision to end production of the A380, citing lack of demand. The firm announced that it would cease to sell the super-jumbo four-engine aircraft and instead shift its long-range focus to the A330-900 and A350-900, both smaller twin-engine aircraft. This strategic shift by Airbus as well as the large order logs for long-range twin-engine aircraft, particularly the 787 and A350, demonstrate a preference among airlines to shift their long-haul fleets for toward smaller aircraft options. While does not in and of itself signal that airlines will use the technology to move toward point-to-point routing, it does mean that if our hypothesis is true, the effects may intensify in the coming years as the smaller aircraft become a larger proportion of the total global fleet (See Appendix A for changes in long-range fleet composition over time).

It is important to investigate the ways in which the introduction of the long-range twin-engine aircraft is impacting the industry at large because a shift in the structure of the industry could have a wide range of downstream impacts on the global economy as a whole. If new aircraft are allowing businesses passengers to reach their destinations more quickly and efficiently, there may be an associated increase in labor force productivity for white-collar jobs. Similarly, more convenient routing options may have an impact on customers' willingness to pay for airline tickets as well as their preferences for air travel as compared with other modes of transportation. If the characteristics of the new aircraft enable nonstop routes between cities that were not formerly directly connected, there could be impacts on the bilateral interactions between the countries that have become connected. An understanding of the ways in which the aviation industry is evolving has ramifications across the larger economy, so it is crucial to observe the empirical impact of new technology that could change the route structure of the industry as a whole.

IV. Data

Due to limitations on available data, analysis was limited to flights originating from or landing in the United States. The United States Bureau of Transportation Statistics (BTS) records data on all city-pair routes for domestic air traffic as well as international traffic in its T-100 data set. We choose to only consider international traffic, as the impact of the new aircraft is rarely if ever felt across the relatively short distances covered by domestic flights. We also excluded flights from American territories such as Guam, as we felt that those flights did not fit into the spirit of our sample due to their geographical separation from the mainland United States.

T-100 international segment data contains a distinct monthly data point for every nonstop segment traveling to or from the United States, with data collection beginning in

1990. We will only use flight data from 1995-2017, chosen to begin in the year of the Boeing 777's introduction and end when data ceased to be available. Beginning in 1995 encloses our data in years that could feasibly have used twin-engine long-range aircraft, though the availability of such aircraft will increase throughout the sample as more aircraft are designed and delivered. The database contains information for each individual segment on the number of flights flown, number of passengers transported, total passenger capacity of the flights, aircraft type, departure and destination cities, and distance between the cities.

Beginning with all segments flown, we then imposed a number of conditions for inclusion in the final data set. First, we condensed all city-pairs to the leg originating in the United States and landing abroad in order to eliminate redundant data points that would double our sample size. Next, we eliminated all flights that were less than 4,500 nautical miles in order to focus only on flights long enough to be realistically served by the emerging technology in question. Additionally, we eliminated segments that were flown fewer than 10 times in a given month and segments carrying fewer than 1000 passengers in a month to avoid flights that were only served for a specific occasion or cargo flights. Finally, we only considered a segment to be served if it fit these criteria at least 4 times in a given year, hoping to eliminate anomalies or segments that were offered and quickly failed. We end with a set of segment years, meaning that each city-pair has an individual data point for each year that it met our criteria from 1995 through 2017.

In order to analyze the characteristics of cities named in the T-100 set, we collected data on the population, GDP per capita, and political significance of each city. We obtained population data from the United Nations' Department of Economic and Social

Affairs. For GDP per capita, we used Metropolitan Statistical Area data from the Bureau of Economic Analysis for the United States leg and data from the International Monetary Fund for the international leg. We were unable to attain city-level GDP per capita data with enough observations to satisfy our data set so we were forced to use national-level GDP per capita data. We feel that this did not have a substantial impact on our outcomes, however, due to the general correlation between city and national wealth and the fact that a majority of cities in our sample contain the lone major international airport in their country and therefore are serving a much larger group of people than city-level data would represent. Additionally, data from the United States Central Intelligence Agency was used to create a dummy for whether a city was its country's capital, hoping to account for a reason that a smaller city may have a large number of international flights.

V. Methods

To begin, we will use the T-100 data to obtain descriptive information regarding how the new aircraft are being used. We predict that characteristics of the technological shock represented by twin-engine long-range jets will result in a use profile that is differentiated from long-range aircraft of the past. In particular, the parallels to the analysis of Brueckner and Pai would suggest that the new aircraft are able to serve segments that would not have been viable for service by four-engine aircraft.

If our hypothesis is correct, flight trends will show that flown segments served by twin-engine aircraft have less "favorable" characteristics than those served by their four-engine counterparts. This is because the new, thinner segments in service would have characteristics that made them unfit for direct flight in the former technology regime.

First, we will compare the populations of the cities connected by both the new twin-engine aircraft and the four-engine aircraft. In accordance with the thin routes hypothesis, we would expect that the geometric mean population of the cities is higher for segments served by four-engine aircraft than for those served by twin-engine aircraft. It is important to note that the use of geometric mean will lead to more pronounced differences when a particularly small city is part of a segment. This will allow for strong expression of a segment containing a small city, as a massive city will not "mask" the average population average of itself and a much smaller city as severely as it would using an arithmetic mean.

After population, we will look at the wealth of cities connected by the segment. Prior research shows that business travelers are more likely to travel nonstop routes and are willing to pay higher ticket prices for them because they have a higher value for the time consumed by connecting flights. Therefore, the destinations that already had long-haul nonstop flights are likely to be the routes containing a higher proportion of business travelers. For this reason, we expect that long-haul segments established and flown only by twin-engine aircraft would be less wealthy cities with relatively lower proportions of business travelers. This stage brings the most concerning aspect of using national level data for the international city. Take China as an example of a potential problem, since the geographic size of the country as well as the number of large urban areas make it likely that multiple cities with very different characteristics and wealth far different from the national average operate nonstop flights to the United States.

After discussing descriptive statistics, we will create a probit model that uses characteristics of a city-pair in order to predict the probability the cities will be connected by a direct flight in a given year. This will be done by first considering each city that has been an endpoint of a qualifying segment month over our sample. This consists of 37 cities in the United States and 102 foreign cities[3]. From this group of cities, we will create a data point for every combination of a United States city and a foreign city in each year. From here, we will create a dummy and assign a value of 1 to city-pairs that were actually connected by a direct flight segment in a given year. This dummy will become the dependent variable of our mode.

While our probit model was generally motivated by Brueckner and Pai, there are crucial considerations for international aviation that require us to use a different methodology. Brueckner and Pai attempted to create a state of the world before the introduction of the regional jet by estimating their probit model in a period of time leading up to the introduction of the regional jet. Using this estimation it predicted the probability of segment connection in the period after the regional jet was introduced and sought to observe whether the segments served by regional jets were less likely to be served by existing aircraft. A lower predicted service probability would imply that the technology was being used to connect segments that were unlikely to previously be linked by direct service.

This method would be difficult to apply to these papers because of heterogeneity of airport use across airlines in international aviation. While Brueckner and Pai could rely on the fact that all major American airlines fly to all major US cities, each airline in our sample will fly either to or from only one its larger hubs. To illustrate how this becomes a

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[3] Certain cities were dropped for data limitation considerations. These cities cumulatively made up less than 0.5% of the qualifying segments. Additionally, cities more than 10,000 miles apart were dropped because there is no aircraft on the market today with the ability to fly over 10,000 miles nonstop.

problem, take the examples of Lufthansa and All Nippon Airways, two of the largest airlines in the world with a number of daily flights to the United States. Lufthansa is one of the largest operators of the four-engine Boeing 747 in the world while All Nippon Airways is the largest operator of the twin-engine Boeing 787. Additionally, Lufthansa's main hub is Frankfurt, a city with under 750,000 inhabitants, while All Nippon Airways' main hub is Tokyo, the largest city in the world with over 36 million residents. Therefore, our sample will show a number of 747-flown segments with a small average population as well as a number of 787-flown segments with a massive average population. This skews our data because the potential ability to offer new segments using the new technology is not constant across cities.

In order to avoid the problem of hubs, we choose to instead create a model that uses the full range of data in estimation. This will allow us to track the influence of the technology as it was progressively introduced and consider the full basket of long-haul flights together. The key aspect of this model will be a variable indicating the availability of twin-engine long-range aircraft, whereby a positive and significant coefficient would indicate that a segment is meaningfully more likely to be flown with more twin-engine aircraft availability than it would be in a market dominated by four-engine jets. For this variable, we used T-100 data to find the number of qualifying months, as described in section IV, flown by each model of aircraft in a given year[4]. Therefore, values of the variable are equal to the number of qualifying segment-months flown by a model in a

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[4] Our first choice would have been to simply use the number of aircraft of each model in service, but T-100 data does not use the include the tail number or any variable that specifies the specific aircraft. Therefore we were not able to use raw number of aircraft and also could not use shipment data due to uncertainty as to which specific aircraft were in use for international flights to or from the United States.

given year rather than the raw number of aircraft, and an individual aircraft may count twelve times for a given year if it flies a qualifying segment each month. We feel that this metric is, given our data constraints, a fair proxy for the number of each aircraft model in service for each year in our sample. For reference, the average number of qualifying route-months by twin-engine aircraft is 1,720 over our sample period.

Statistical significance of our technology variable would indicate that thin routes are being flown with increasing frequency in a manner that transcends the simple increase in number of flights. This is because the value of the technology variable will grow over time not as a portion of all flights but rather as a gross number. This means that a positive value will indicate that city-pairs become more likely to be connected by a direct flight as a result of increased availability of long-range twin-engine aircraft. This revelation would imply a causal link between availability of the new technology and the uptick in segments served.

In addition to our technology variable, the explanatory variables in the probit model will be the geometric mean of the populations of the cities, the distance between the cities, the geometric mean of the GDP per capita of the two cities as described above, and a dummy for whether the international city in the segment is the capital of its country. Additionally, a dummy variable will be included to indicate whether the US city in the city-pair is in Alaska or Hawaii. This is done because we feel that the large number of segments from either Honolulu or Anchorage, especially in the early years of the sample when twin-engine jets had more limited ability to cross oceans, is a result of the geographic locations of the cities rather than characteristics that typically make a city an attractive destination for flights.

The form of our probit model is:

$$\Pr\,(Y_{i,j,k} = 1) = \Phi(\beta_0 + \beta_1 POP_{i,j} + \beta_2 GDP_{i,j} + \beta_3 DIST_{i,j} + \beta_4 CAPITAL_j + \beta_5 AK\_HI_i \quad + \beta_6 TECH_k + \varepsilon_{i,j,k})$$

In the model, $Y_{i,j,k}$ is equal to 0 if there is not a nonstop flight along route i,j in year k and equal to 1 if there is such a flight. $POP_{i,j}$ is the geometric mean population of the city-pair i and j. $GDP_{i,j}$ is the mean GDP per capita of i and j. $DIST_{i,j}$ is the distance between i and j. $CAPITAL_j$ is equal to 1 if j is the capital city of its country and 0 if it is not. AK_HI_i is equal to 1 if i is in Hawaii or Alaska and 0 if it is not. Finally, $TECH_k$ is our proxy for the availability of the new technology in year k. The output of our probit model is the probability that $Y_{i,j,k} = 1$ in year k given the characteristics of city-pair i,j.

To check the robustness of our results, we first intend to analyze multiple baskets of aircraft as representing the emerging technology. This is because while there are a number of long-range twin-engine aircraft in service, the size and efficiency of those aircraft can vary considerably. For example, a Boeing 777 seats 317 people under its basic configuration while a Boeing 787 seats just 242. While both aircraft are substantially smaller than their four-engine counterparts, the 787 as well as certain A330 models much more clearly express the technological shift in the industry that is at the heart of this study. Therefore, we would like to estimate our probit model using different baskets of aircraft to see whether our hypothesis applies only to extremely efficient aircraft or to all twin-engine models.

Next, we will estimate our probit model while excluding the technology variable, opting to see the change over time in estimates using only the other independent variables. Given that the mix of long-range aircraft has shifted heavily toward the twin-engine aircraft models in the past two decades, it would be encouraging for our hypothesis if the average probit estimates for flown segments have decreased over the years. This would indicate that the route mix has shifted toward segments that were less likely to be flown over the entire sample.

Finally, we will estimate our original probit model with time dummies included to measure the extent to which changes are a result of the technological advances as opposed to broader shifts in industry practice. We hope that the increase in twin-engine aircraft availability will remain a significant factor even in light of broader changes in the industry over time, but feel that it is important to ascertain whether variation in routing patterns across years will lead to a loss of significance.

VI. Results

Descriptive statistics seem to support our hypothesis regarding how the characteristics of served segments have evolved over time. While it is not clear whether the technological shocks in the industry are the driving factor behind these changes, our data is encouraging in that it shows that changes to average segment characteristics are in the direction that would be consistent with the thin routes hypothesis of Brueckner and Pai.

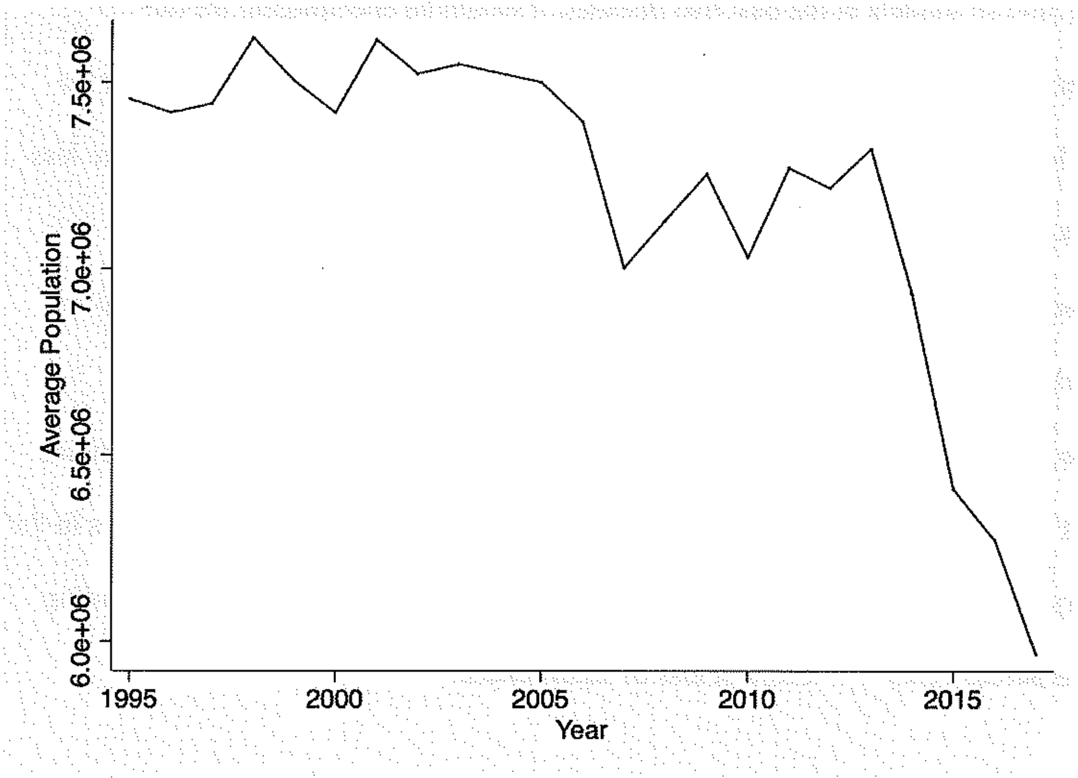

Figure 2: Change in Average City Population, 1995-2017

We begin with the change in average population of city-pairs that have been flown over the last 20 years (Figure 2). We can see a sharp decline in the geometric average of city populations, with a particularly precipitous drop in the past 5 years. This decline, and in particular the timing of the decline, is extremely encouraging as the steep decline seems to coincide with the introduction of the smallest and most efficient of the twin-engine long-range aircraft, the Boeing 787. Figure 3 shows the population change graph overlaid with the number of qualifying segment months flown by the 787. We can see that the sharp decline in average population is correlated quite strongly in an inverse manner with the introduction of the 787. Because the 787 is the most extreme example to date of a smaller long-range jet, the fact that the observed change coincides with its introduction could be an indicator that airlines are using the new technology in ways distinctly different from older aircraft.

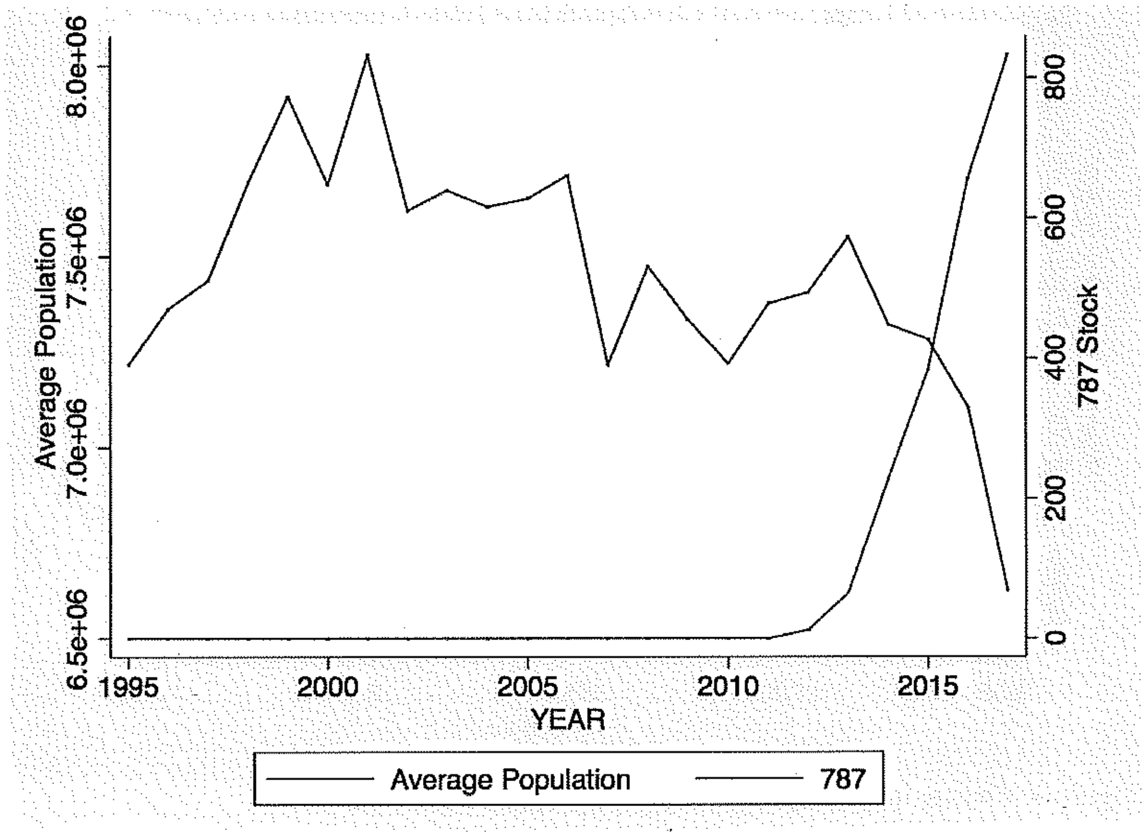

Figure 3: Change in Average City Population with Introduction of Boeing 787

Next we consider the change in average GDP per capita of the city-pair (Figure 4). Here we also see a decline over time, which also seems to agree with the population result in its consistency with our hypothesis. We see a similar drop over the sample, however in this case the decline is seen over a longer time period and also in different years. It would be interesting to find the extent to which the decline is influenced by the spike in flights to China from the West Coast of the United States, as China's national GDP per capita is likely far lower than that of cities that are home to international, transoceanic flights. However, the impact of China alone is unlikely to cause a drop of nearly 10% in a decade, so the decline may still be attributed to the technological shift.

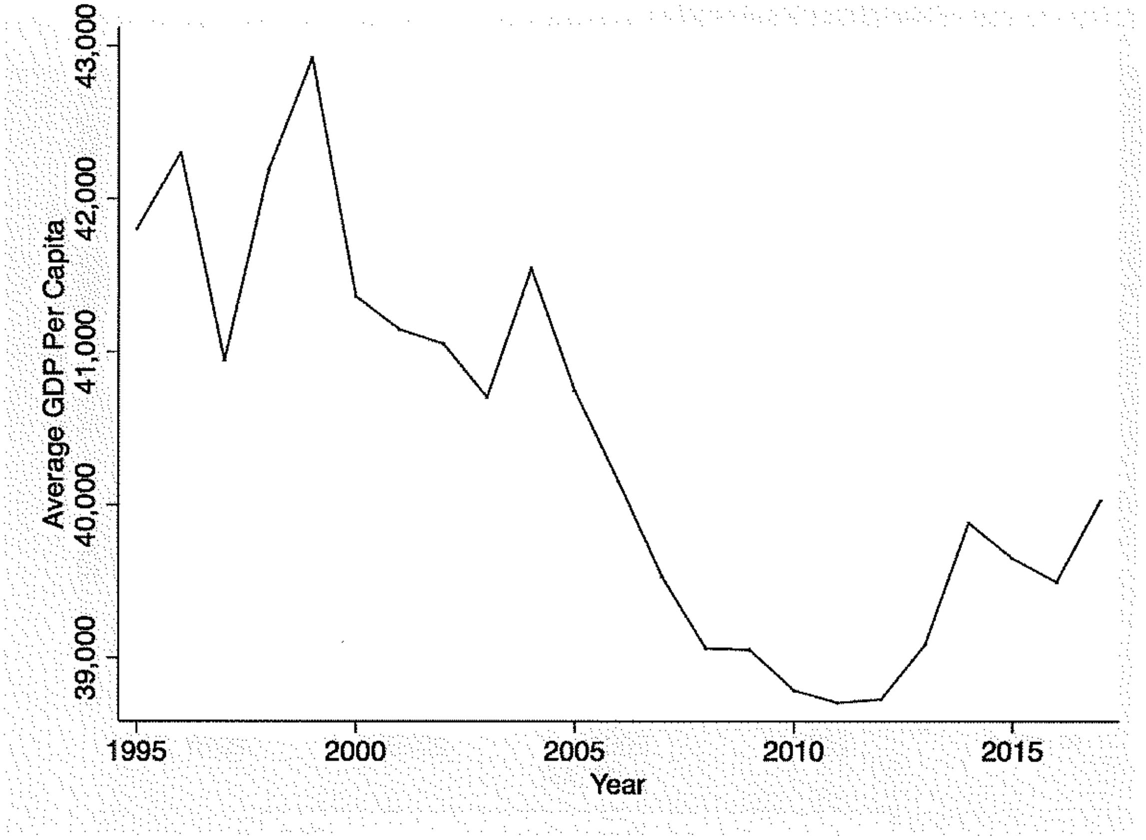

Figure 4: Change in Average City GDP Per Capita, 1995-2007

While not directly related to our core hypothesis, a final descriptive statistic that we found to be noteworthy was the change in load factor, or the proportion of seats filled on a flight, over time. Figure 5 shows the way in which the average load factor has shifted over our sample, showing an increase of about 20%. This is of interest because, while it is natural that the aviation industry in general ought to become more efficient over time, it is quite possible that the smaller available aircraft have driven some of this change. It is intuitive that an airline would be able to more efficiently fill its aircraft when it does not need as many demanding passengers to operate a profitable flight, so it is possible that the smaller aircraft available to make long-haul flights have contributed to an increased load factor across the industry.

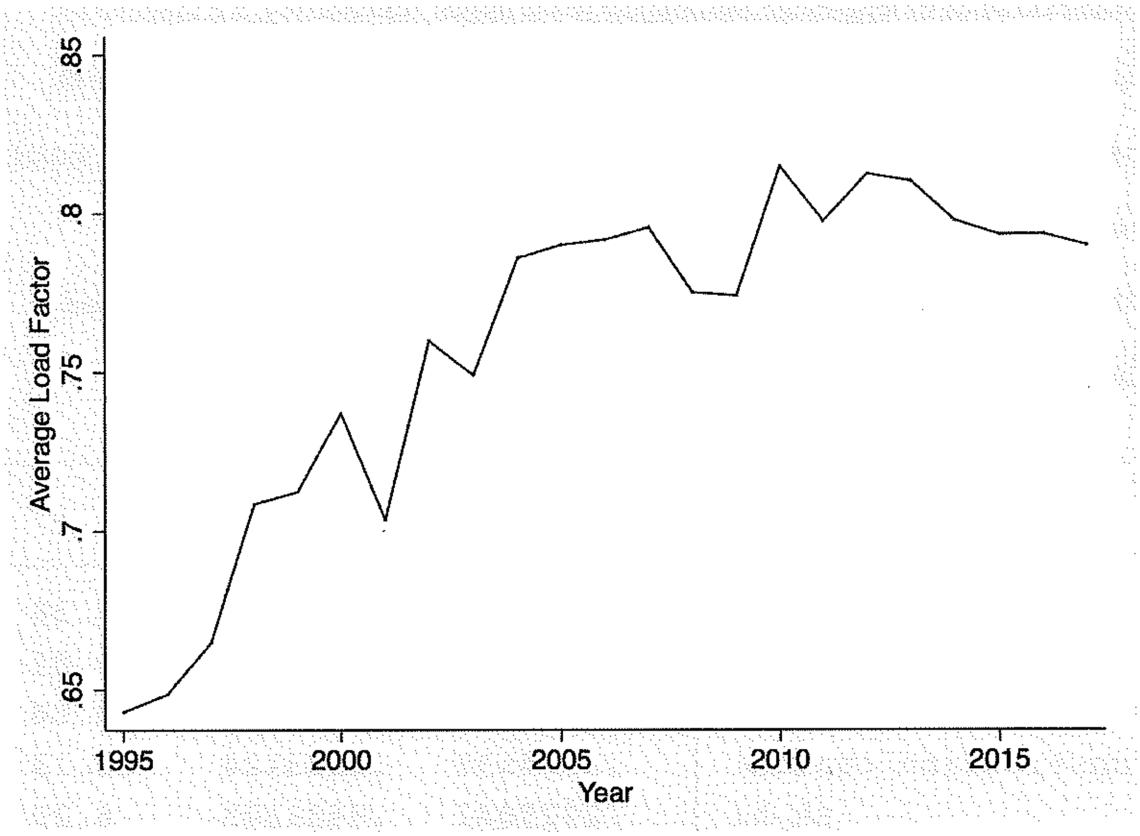

Figure 5: Change in Average Flight Load Factor, 1995-2017

Turning to the probit model, we find that each explanatory variable in the main probit (Table 3[5]) has the sign expected by the theory and that all are statistically significant. In particular, we find that the probability of a direct flight decreases as distance increases, increases as population increases, increases as GDP per capita increases, increases when the destination is its country's capital, and increases for cities in Alaska and Hawaii.

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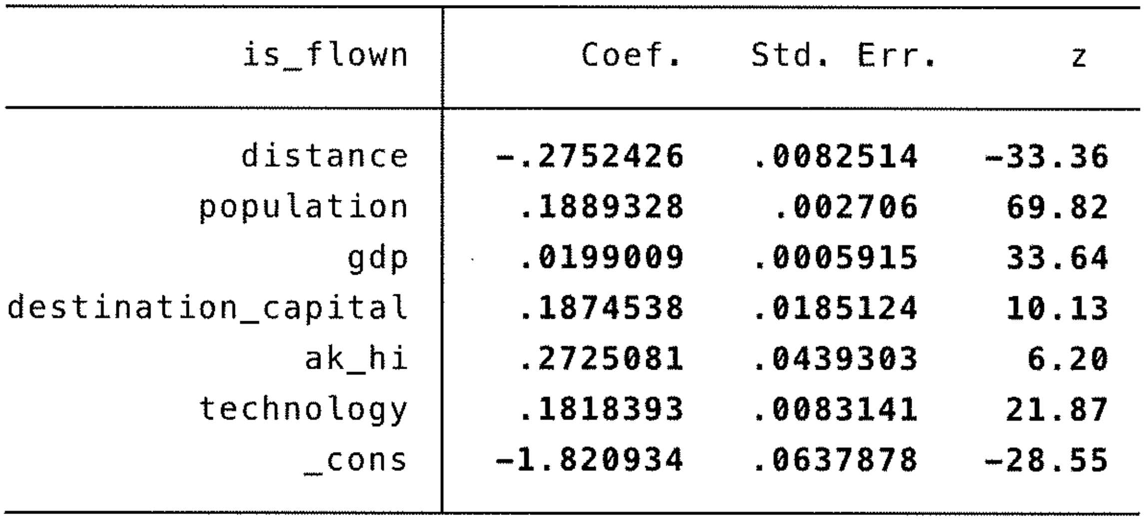
[5] Note that for clarity of coefficients, all output tables express distance in thousands of Nautical Miles, Population in millions, GDP per capita in thousands, technology stock in thousands of segment-months, and stock value of individual aircraft in hundreds of segment-months.

Finally, and most importantly, we see a positive and statistically significant value for our technology variable, indicating that a given route is more likely to be served directly when the stock of long-range twin-engine jets is larger. Additionally, we find that the average predicted value for segments that did have service in a given year was 0.239 while that for the segments with no service was 0.0481, a reassuring sign that our model was able to

show a substantial difference in characteristics between segments that are flown and those that are not.



```
           is_flown |      Coef.   Std. Err.      z
--------------------+--------------------------------
           distance |  -.2752426    .0082514   -33.36
         population |   .1889328     .002706    69.82
                gdp |   .0199009    .0005915    33.64
destination_capital |   .1874538    .0185124    10.13
              ak_hi |   .2725081    .0439303     6.20
         technology |   .1818393    .0083141    21.87
              _cons |  -1.820934    .0637878   -28.55
```

Table 3: Probit Results for Main Model

With such a large data set, the statistical significance of our result, while important and encouraging, does not tell the whole story without discussion of its magnitude. To this end, we look to the marginal effects (Table 4). At the means of our explanatory variables, we find that the marginal effect of an increase of our technology variable by 1000 increases the likelihood of a flown segment by 1.08%. When one considers that the mean value of our technology variable is about 1,720, the marginal effect at mean value is about 1.86%. In the context of a model with mean predicted value of 5.96% over the sample, this shows quite a substantial increase due to the emergence of the new technology.

```
variable |      dy/dx    Std. Err.       z
---------+--------------------------------
distance |   -.0162925       .00049   -33.12
popula~n |    .0111835       .00023    47.62
     gdp |     .001178       .00004    32.25
destin~l*|    .0114076       .00117     9.76
   ak_hi*|    .0204503       .00407     5.02
techno~y |    .0107636        .0005    21.49
```

Table 4: Marginal Effects for Main Probit Model

To check the robustness of our main result, we turn to a variant of our central probit model to look at specific models of aircraft that more fully embody the theory of our technological shock, albeit making smaller up a smaller proportion of the overall aircraft in service. Specifically, the Boeing 787, while lacking market share due to its recent introduction, is the most efficient long-range twin-engine aircraft to date and has a long backlog of orders ensuring that it will increasingly disrupt the aircraft mix of long-range aviation. The 787 is far smaller than any long-range jet introduced before it; the 777, which was the first plane to gain massive market share as a long-range twin-engine jet and makes up a large portion of our twin-engine segment data, holds about 50% more passengers than the 787 while operating at similar service ranges. Our descriptive statistics showed that the 787's introduction has a strong correlation with a drop in average populations among served city-pairs. To test the impact of only the extreme case of our technological shift, we consider only data points from 2011-2017, as the 787 first appears in our sample in 2012, and run our probit once again.

Our results[6] (Table 5) indicate that even using a much smaller sample and only considering a single aircraft model with limited stock relative to the overall industry, we find statistically significant positive results for the technological shock to the industry. Additionally, the marginal effects of the model (Table 6) show that the 787's impact sits at about 0.85%, which stands impressive when one considers that the stock of these aircraft as a percentage of the overall market remains quite small.

is_flown	Coef.	Std. Err.	z
distance	-.216062	.0124248	-17.39
population	.1952579	.0046024	42.42
gdp	.0204248	.0009357	21.83
destination_capital	.1928738	.029653	6.50
ak_hi	.0996948	.0772604	1.29
B787	.0287325	.0047297	6.07
_cons	-1.772517	.0980102	-18.09

Table 5: Probit Results for Data since 2011 with 787 Variable

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[6] In addition to encouraging results about the 787's significance, it is reassuring to see that the dummy variable for Alaska and Hawaii is no longer significant in this probit. This supports our assertion that flights to these destinations prior to the introduction of the new technology were more the result of their geographical location than underlying desirable characteristics.

variable	dy/dx	Std. Err.	z
distance	-.0204409	.00116	-17.61
popula~n	.0184727	.00053	34.56
gdp	.0019323	.00009	22.17
destin~l*	.0186897	.00295	6.33
ak_hi*	.010168	.00848	1.20
B787	.0027183	.00045	6.08

Table 6: Marginal Effects Looking at only 787 Flights

Next, we consider the trends in our model's estimates over time. With this in mind, we used our original probit coefficients to calculate the average predicted value for all segments served in each year. Figure 6 shows our results; there is a clear trend illustrating a decline in estimated values over the course of the sample, and since 2005 in particular. This is encouraging, as it tells us that the city-pair served became, according to our model, less suited for direct flight over the course of our sample. When one considers that this shift has coincided with a massive increase in the availability and market share of twin-engine long-range aircraft, the trend indicates that the direct segments in service have become thinner in the time since the long-range twin-engine aircraft was introduced.

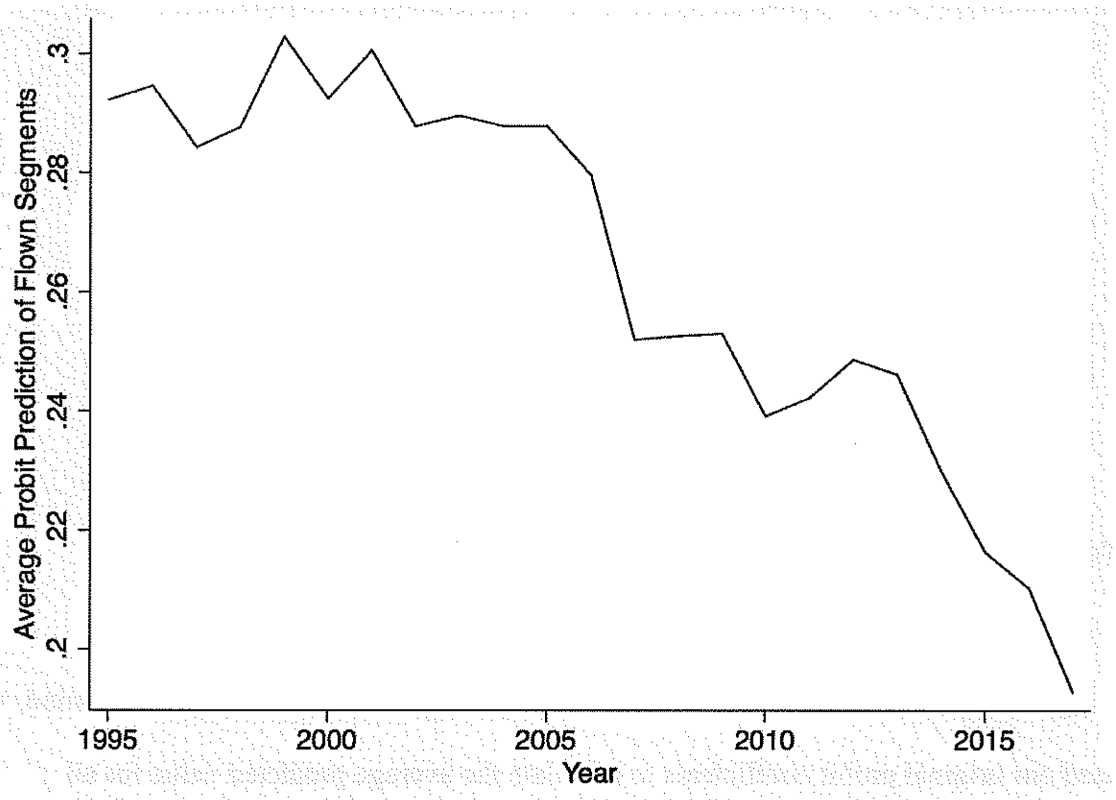


Figure 6: Change in Probit Estimations of Segment Service Probability, 1995-2017

Finally, we check the impact of our results when time dummies are added for each year. Table 7 shows the probit results with these dummies. As could be expected, the early years when relatively few segments were served see the largest coefficients in magnitude in the negative direction. As the years progress the dummies' coefficients become less negative and even become positive in direction for some of the later years in the sample. However, when year dummies are included our technology variable is no longer statistically significant. While it is encouraging that the sign of the variable remains positive, the lack of significance casts some degree of doubt on the causal nature of the new technology's impact on the shift of airlines' international route networks.

is_flown	Coef.	Std. Err.	z
distance	-.2754872	.0082557	-33.37
population	.1890444	.002708	69.81
gdp	.0199087	.0005917	33.65
destination_capital	.187609	.0185187	10.13
ak_hi	.2734198	.0439264	6.22
technology	.1540106	.1204274	1.28
yeardu1	-.1636998	.4171669	-0.39
yeardu2	-.140623	.4146686	-0.34
yeardu3	-.0977116	.4088428	-0.24
yeardu4	-.0676942	.4001023	-0.17
yeardu5	-.0560286	.3836601	-0.15
yeardu6	-.0021038	.3711286	-0.01
yeardu7	-.0115228	.3526183	-0.03
yeardu8	-.0822886	.3574268	-0.23
yeardu9	-.0894127	.3440645	-0.26
yeardu10	-.0690662	.3350224	-0.21
yeardu11	-.0638891	.3157856	-0.20
yeardu12	-.0309004	.2931195	-0.11
yeardu13	.0004957	.2633564	0.00
yeardu14	.0098176	.2327412	0.04
yeardu15	.0069356	.2244808	0.03
yeardu16	-.0060515	.1974427	-0.03
yeardu17	-.0173858	.1687749	-0.10
yeardu18	-.0056006	.1618759	-0.03
yeardu19	-.0090281	.1497973	-0.06
yeardu20	.0014515	.1190716	0.01
yeardu21	-.0093598	.080447	-0.12
yeardu22	0	(omitted)	
yeardu23	0	(omitted)	
_cons	-1.734653	.4674236	-3.71

Table 7: Probit Results with Inclusion of Year Dummy Variables

VII. Discussion

While we are encouraged by the main results of this paper and their congruence with our theoretical hypothesis, we feel that further research could strengthen its findings with the addition of newer and more precise data. Most notably, many of the findings of this paper are somewhat "too soon" in the sense that the most efficient aircraft, most notably the Boeing 787 and Airbus A350, do not yet have a substantial share of the market due to the substantial time required to producing new aircraft. Therefore, we feel that if the central findings of our research are indeed true, the effects will become more and more pronounced in coming years as the efficient aircraft gain market share and as frictional limitations on airlines' ability to alter their route networks subside over time.

Additionally, more precise data would have allowed for our research to conform more closely to Brueckner and Pai's theoretical model. In particular, city-level data for international GDP per capita would have enabled us to more clearly see how the wealth of a city reflects its ability to sustain international flights. This rings especially true for developing countries containing cities with very wealthy residents while the rest of the country lags far behind; China and India are the best example of this potential issue. Also, the ability to identify aircraft by tail number and, therefore, create a precise measure of the number of aircraft in service, would allow us to more clearly understand the penetration of new technology over time.

The failure of our technology variable to remain significant in the model that includes year dummies also may be attributable to the problems mentioned above. We wonder whether the results may have been different with the ability to identify aircraft by tail number rather the alternative we used due to data constraints. More broadly, for all models it is possible that we could have obtained enhanced results with greater data availability. We feel that metrics similar to those used by Brueckner and Pai could not easily be obtained on the international level but could leave to models that more precisely estimate the contributing factors in airlines' routing decisions.

Finally, we are interested in how our results may relate to the macroeconomic environment of the past decade. In particular, aviation is a cyclical industry that is known to struggle in adverse macroeconomic conditions. Therefore, it is possible that some of the growth and change shown in our data may be at least partly attributed to the relatively steady global economic conditions of the past decade. This effect would be intensified by the sustained low cost of jet fuel, which substantially reduces airline costs, especially for long-haul flights. We are interested to find whether these effects persist through a full economic cycle, as a large portion of our observed changes comes after 2009 during the extended period of macroeconomic stability.

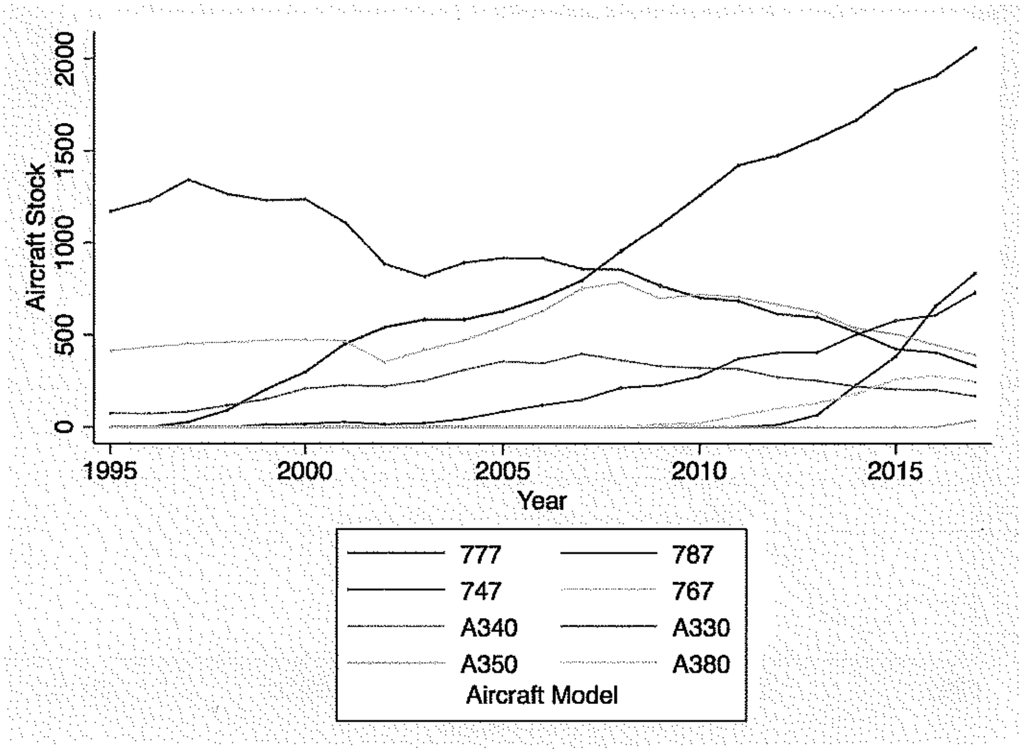
VIII. Conclusion

We use T-100 international segment data to ascertain whether the introduction of the long-range twin-engine jet has fundamentally changed the way in which airlines create their direct international flight networks. While large four-engine jets have historically served these segments, we suspect that the introduction of aircraft capable of flying such long distances while carrying fewer passengers could make new segments economically viable for the first time. Descriptive statistics show encouraging results as the characteristics of city-pairs with direct flight service, such as average population and GDP per capita, have become less "desirable" in the past two decades. We test this hypothesis by creating a probit model predicting the likelihood of a direct flight connecting cities based on the availability of long-range twin-engine aircraft as well as metrics describing city-pairs that we feel would make them more or less desirable for direct service.

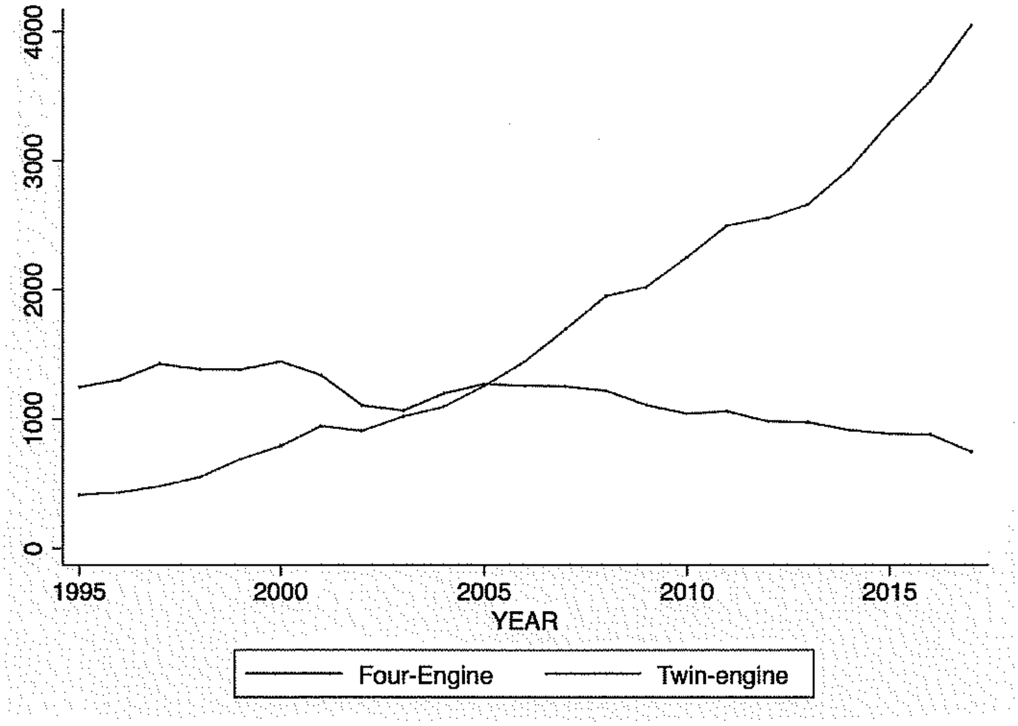
Our main probit results show a positive, statistically significant correlation between the increase in twin-engine aircraft availability and probability that a given segment was served by a direct flight. Marginal effects show that probability of service is 1.86% higher at the mean stock of twin-engine aircraft in the sample. Additionally, the test delivers significant results when only the Boeing 787 is considered. This is significant because the 787 is the strongest manifestation of the technological shift and was released in 2011, indicating that it has had a material impact even in limited service time and while representing a small share of the overall market. A model estimated without the technology variable shows that the average probit estimate for segments in service has declined over the sample, indicating that the segments in service have become less desirable by our metrics as the twin-engine technology has been rolled out. While all of these results are encouraging, a model with year dummy variables undermines our hypothesis as the twin-engine stock variable becomes statistically insignificant.

Overall, we are encouraged by our results and feel that the availability of twin-engine long-range aircraft will continue to drive changes in international aviation routing. Improved data could strengthen our results and allow us to estimate a more precise model, but we feel that our analysis shows a clear connection between the rise of the new technology and shifts toward service of thinner routes. Robustness checks cast some doubt on the causal nature of the technological shock, but it is logically sound and borne out by our analysis that the ability to serve long-distance segments with fewer passengers has unlocked economically viable routes that were not previously feasible.

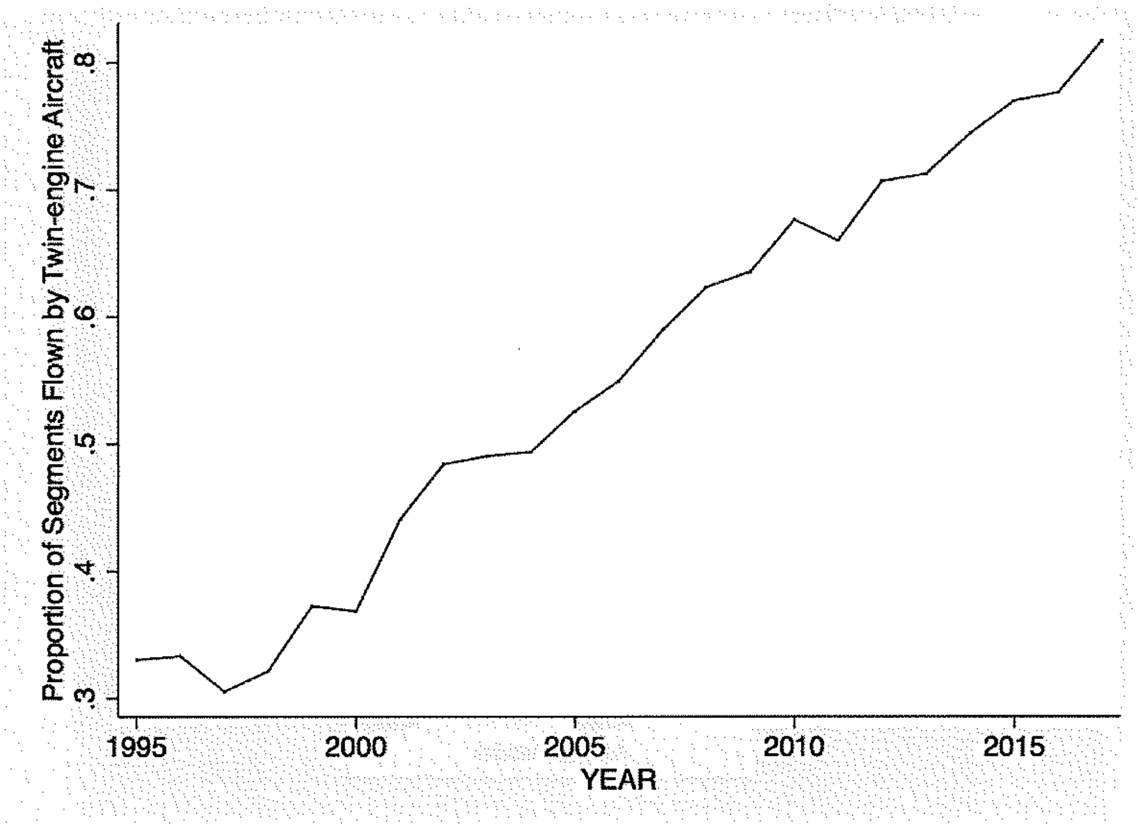
Appendix A: Changes in Overall Fleet Composition, 1995-2017



Qualifying Segment-months Flown by Aircraft Model, 1995-2017



Qualifying Segment-months Flown by Number of Engines, 1995-2017



Proportion of All Segments Flown by Twin-engine Jets, 1995-2017

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