

Evaluation of Regional Jet Operating Patterns in the Continental United States

By Aleksandra Mozdzanowska and R. John Hansman

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Abstract

Airlines are increasingly using regional jets to better match aircraft size to high value, but limited demand markets. The increase in regional jet usage represents a significant change from traditional air traffic patterns. To investigate the possible impacts of this change on the air traffic management and control systems, this study analyzed the emerging flight patterns and performance of regional jets compared to traditional jets and turboprops. This study used ASDI data, which consists of actual flight track data, to analyze flights between January 1998 and January 2003. In addition, a study of regional jet economics, using Form 41 data, was conducted in order to better understand the observed patterns.

It was found that in 1998 US regional jet patterns and utilization closely resembled those of the turboprops. Both aircraft were used for hub feeder operations. They flew relatively short distances, under 500 nautical miles, and exhibited similar cruise altitudes and speeds. These patterns began to change as the number of regional jets increased. By January 2003, the regional jets were no longer used solely for hub feeder operations, but were flying longer routes at higher altitudes and faster speeds than turboprops. As a result, regional jets have come to fill a gap in the market by flying on longer routes than the turboprops, but shorter than the narrow body jets.

An economic analysis was conducted in order to better understand the observed regional jet patterns. It was found that regional jets have lower operating costs per trip and higher operating costs per ASM than traditional jets. As a result, regional jets are currently a lower cost alternative for traditional airlines because they cover the cost of regional jet flights on a per departure basis. However, if this structure were to change regional jets would become a less appealing alternative. To better understand the consequences of a change in the operation patterns, changes in the cost of regional and traditional jets were analyzed when trip length and pilot costs per block hour were normalized. It was found that regional jet costs per trip are very similar to traditional jet costs per trip when the trip length between the two aircraft categories is normalized, but that the normalization of pilot cost per block does not have a significant effect on the relative costs of the two aircraft types.

In 2003, the US regional jet operations showed a high density of flights in the north-eastern part of the country. This part of the US also has the largest concentration of traditional jet operations; this interaction may result in congestion problems since the two types of aircraft exhibit different performance. In particular, regional jets were observed to exhibit lower climb rates than traditional jets, which may impact air traffic control

handling and sector design. It was also observed that as regional jets replace turboprops, they compete for runways and take off trajectories with narrow body jets. The combination of the different performance and the competition for resources between regional and other jets may result in increased delays and congestions as well as increased controller workload.

The future growth of regional jets is uncertain. However, currently both US Airways and Jet Blue have placed orders for new Embraer aircraft indicating that the growth of regional jets will continue for the time being. In addition, both Embraer and Bombardier are currently designing and manufacturing larger regional jets. These aircraft will be designed to accommodate more passengers on further trips and as a result will further change the composition and performance capabilities of the national fleet.

Acknowledgements

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Abbreviations

ARTS	Automated Radar Track System
ASDI	Aircraft Situational Display to Industry
ATA	Air Traffic Aerospace Laboratory
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
NAS	National Airspace System
OAG	Official Airline Guide
WTO	World Trade Organization

Airport Abbreviations

ATL	Hartsfield - Jackson Atlanta International Airport (Atlanta, GA, USA)
BNA	Nashville International Airport (Nashville, TN, USA)
BOS	General Edward Lawrence Logan International Airport (Boston, MA, USA)
BWI	Baltimore-Washington International Airport (Baltimore, MD, USA)
CLE	Cleveland-Hopkins International Airport (Cleveland, OH, USA)
CLT	Charlotte/Douglas International Airport (Charlotte, NC, USA)
CVG	Cincinnati/Northern Kentucky International Airport (Cincinnati, OH, USA)
DCA	Ronald Reagan Washington National Airport (Washington, DC, USA)
DEN	Denver International Airport (Denver, CO, USA)
DFW	Dallas/Fort Worth International Airport (Dallas-Fort Worth, TX, USA)
DTW	Detroit Metropolitan Wayne County Airport (Detroit, MI, USA)
EWR	Newark Liberty International Airport (Newark, NJ, USA)
FLL	Fort Lauderdale/Hollywood International Airport (Fort Lauderdale, FL, USA)
IAD	"Washington Dulles International Airport (Washington, DC, USA)
IAH	George Bush Intercontinental Airport/Houston (Houston, TX, USA)

IND	Indianapolis International Airport (Indianapolis, IN, USA)
JFK	John F Kennedy International Airport (New York, NY, USA)
LAS	Mc Carran International Airport (Las Vegas, NV, USA)
LGA	La Guardia Airport (New York, NY, USA)
MCI	Kansas City International Airport (Kansas City, MO, USA)
MCO	Orlando International Airport (Orlando, FL, USA)
MDW	Chicago Midway International Airport (Chicago, IL, USA)
MEM	Memphis International Airport (Memphis, TN, USA)
MIA	Miami International Airport (Miami, FL, USA)
MSP	Minneapolis-St Paul International Airport (Minneapolis, MN, USA)
ORD	Chicago O'Hare International Airport (Chicago, IL, USA)
PDX	Portland International Airport (Portland, OR, USA)
PHL	Philadelphia International Airport (Philadelphia, PA, USA)
PHX	Phoenix Sky Harbor International Airport (Phoenix, AZ, USA)
PIT	Pittsburgh International Airport (Pittsburgh, PA, USA)
RDU	Raleigh-Durham International Airport (Raleigh/Durham, NC, USA)
SAN	San Diego International Airport (San Diego, CA, USA)
SEA	Seattle-Tacoma International Airport (Seattle, WA, USA)
SFO	San Francisco International Airport (San Francisco, CA, USA)
SJC	Norman Y. Mineta San Jose International Airport (San Jose, CA, USA)
SLL	Mc Carran International Airport (Las Vegas, NV, USA)
STL	Lambert-St Louis International Airport (St Louis, MO, USA)
TEB	Teterboro Airport (Teterboro, NJ, USA)
TPA	Tampa International Airport (Tampa, FL, USA)

1 Introduction

1.1 Objective

Since 1993, one of the significant changes to the national air space system has been the emergence of regional jets. This growth may have unpredicted consequences on the National Airspace System. The goal of this thesis is to analyze, compare, and understand the national flight patterns and performance characteristics of regional jets, narrow body jets, wide body jets, and turboprops, and to identify the possible implications of regional jet growth for Air Traffic Management and Control.

1.2 Motivation

Regional jets were first introduced in the USA in June 1993 when Comair introduced service between Cincinnati and Akron/Canton [1]. Since that time regional jets have experienced a tremendous growth in the USA. This growth can be seen in Figure 1, which shows the registration data between the first quarter of 1995 and the first quarter of 2004, for the regional jets commonly flown in the United States. The figure shows the sum of all the registrations of each aircraft type in each quarter. It can be seen that the growth between 1995 and 2004 is significant and exhibits a nearly exponential pattern. The two most popular regional aircraft, the E145 and the CRJ2, grew the fastest in this time period. Looking at flight track data, this growth in the number of registrations translated to approximately a 356% increase in regional jet flights in the United States between January 22nd 1998 and January 9th 2003. In 1998 there were 1761 regional jet flights serving 625 origin-destination pairs, and in 2003, these numbers increased to 6263

regional jet flights serving 2140 origin-destination pairs. In comparison, in 1998 traditional jets flew 19545 flights connecting 6275 origin-destination pairs, and in 2003 traditional jets flew 18850 flights connecting 7058 origin-destination pairs.

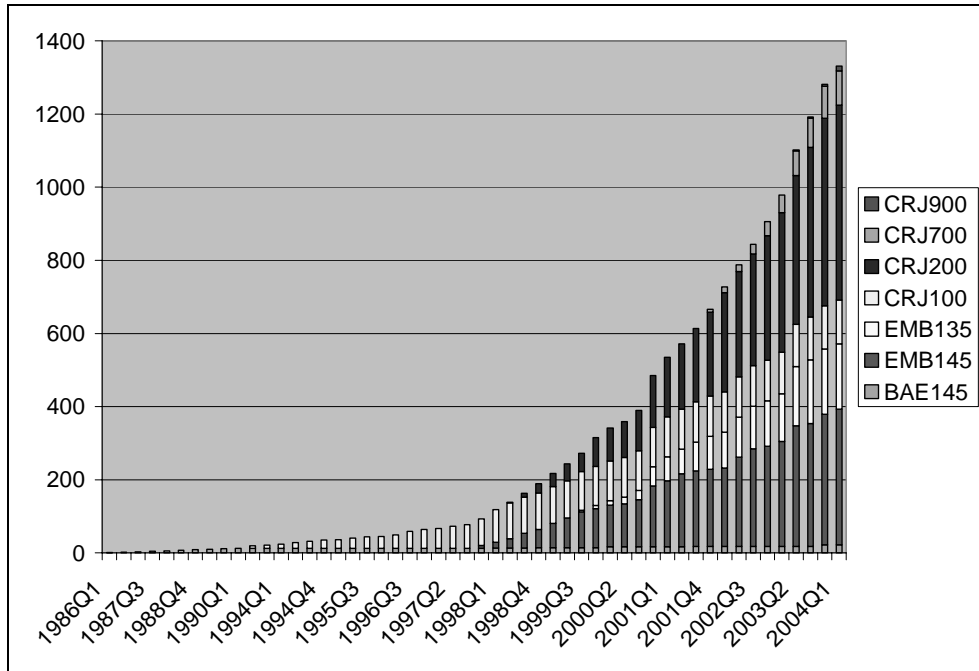


Figure 1: US Regional Jet Growth Based on FAA Registration Data [2]

1.3 Background

Regional jets are generally defined as aircraft powered by jet engines, having between 30 and 100 seats, and capable of flying distances of 800 to a 1,000 nautical miles. The list of regional jets along with the corresponding manufacturers and status of service and production can be seen in Table 1.

Table 1: Regional Jets and Manufacturers

Manufacturer	In service, but no longer produced	In service and currently produced	Not yet in service
Bombardier		CRJ1, CRJ2, CRJ7, CRJ9	
British Aerospace	RJ70, RJ85, RJ100, BAe146		
Embraer		ERJ135, ERJ140, ERJ145	ERJ170, ERJ175, ERJ190, ERJ195
Fairchild Dornier	328JET		328JET (production is to resume)

Aircraft manufactured by Bombardier and Embraer are currently the most commonly flown regional jets in the USA. In particular the Embraer 145 (E145) and the Bombardier 200 (CRJ2) are the two most numerous aircraft in the US regional jet fleet. In 2003, there were slightly fewer than 400 E145 aircraft and slightly more than 400 CRJ2 aircraft, which together account for 65% of the total registered regional jets and for over 50% of all regional jet flights in the United States. Pictures of the two aircraft as well as three view diagrams can be seen in Figures 2 through 4.



Figure 2: Examples of an E 145 (50 seats) and CRJ 2 (50 seats) [3][4]

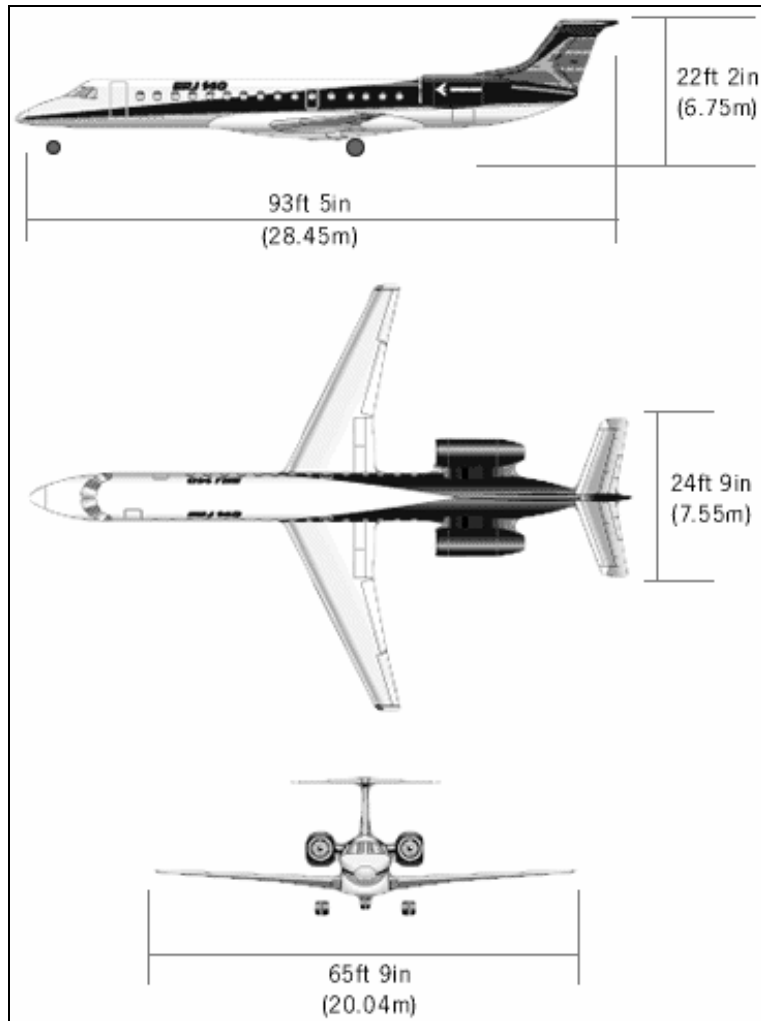


Figure 3: 3-view Drawing of E145 [3]

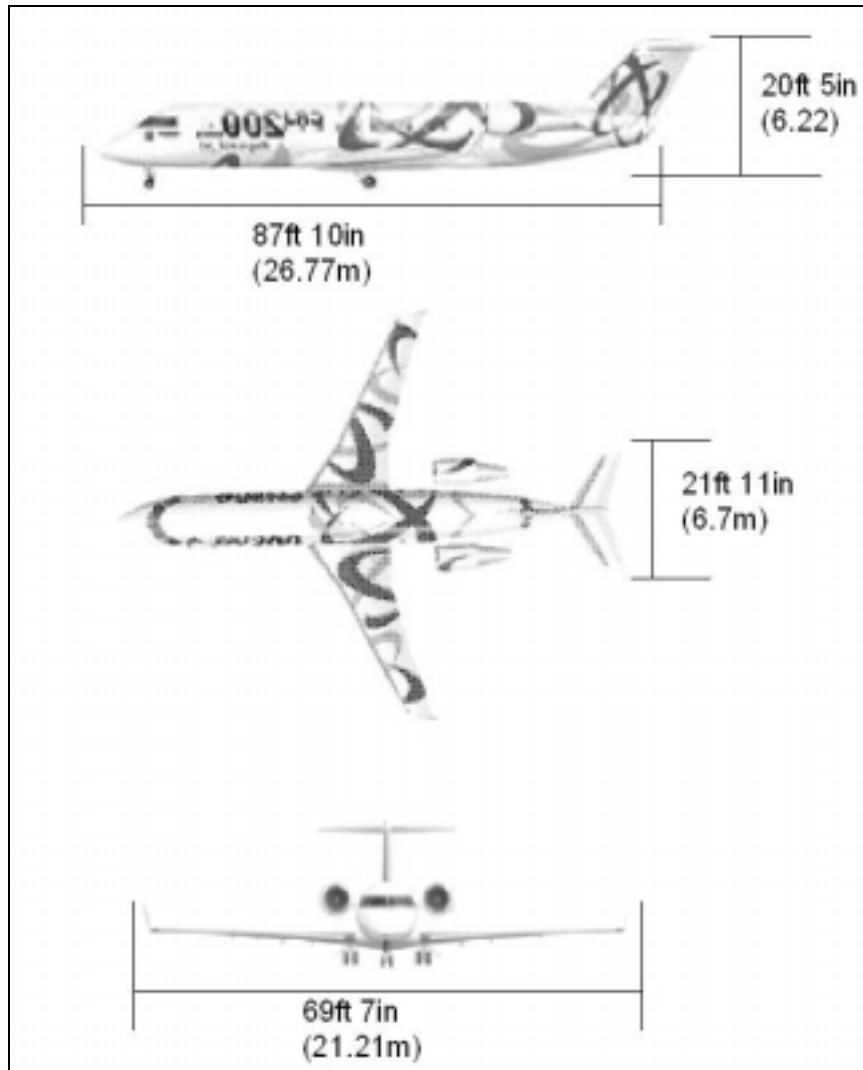


Figure 4: 3-view Drawing of CRJ2 [4]

To provide a better understanding of how regional jets compare to other aircraft currently flow in the United States Table 2 shows the specifications for the E145, the CRJ2, the B190, and the B737-300 (B733). The B190 and B733 are currently the turboprop and narrow body jet aircraft with the highest frequency of flights in the US. It can be seen from the specifications that the regional jets are smaller, lighter, and carry fewer passengers than the narrow body jet. However, the two aircraft types exhibit

similar performance. The regional jets are also much larger than the turboprops, which fly slower and require a much shorter take off and landing field length.

Table 2: Specifications for E145, CRJ2, and B733 [5][6][7]

Aircraft Type	B190	E145	CRJ2	B733
Manufacturer	Raytheon	Embraer	Bombardier	Boeing
Number of Crew	2	2	3	2
Number of Passengers	19	50	50	126
Wing Span (ft)	54.5	65.8	69.7	94.8
Wing Area (sq. ft)	303	551	520.4	980
Max Length (ft)	57.9	98	87.1	109.6
Max Height (ft)	14.3	22.1	20.5	36.5
Empty Weight (lb)	10150	26270	30500	72360
Gross Weight (lb)	16600	45415	47450	124500
Max Landing Weight (lb)	16100	42549	47000	114000
Cargo Capacity (lb)	5880	2646	13500	12800
Engine Model and Make	PWC PTA6A-65B	2 All. AE3007- A1/1 or -A1	2 GE CF34-3B1	2 CMF56-3C-1
Max Speed (Mach or mph)	M0.4	M0.78	M0.81	0.74
Best Cruise Speed (Mach or mph)	M0.4	M0.76	M0.74	M0.745
FAA Take off Field Length (ft)	3800	5839	5800	6660
FAA Landing Field Length (ft)	2450	4495	4670	4580
Still Air Range (mi)	1925	1830	1892	2600

2 Methodology

2.1 Analysis Outline

The first goal of this study was to analyze and understand regional jet growth, evolution, and operating patterns. This goal was reached in two steps. The first was to analyze the data and develop methods to visualize and quantify the change in patterns of regional jet flights. Once this was accomplished aircraft economics, aircraft utilization, airline scope clause agreements, and other factors were used to develop an understanding and explanation of the observed patterns.

The second goal of the study was to assess the validity of common concerns about the impact of regional jets on congestion and air traffic control and management. The concerns were based on the belief that regional jets perform differently than other aircraft. As a result, cruise altitudes, cruise speeds, and climb rates of regional jets and other aircraft were compared. Once the performance of the regional jets and other aircraft was known, areas where the performances differed were identified and studied in more detail.

2.2 Data Sources

To accomplish the goal of analyzing the emerging regional jet trends and conducting a performance comparison between regional jets and other aircraft, this study required flight data for regional jet and other aircraft flights. However, where previous studies have used scheduled flight data such as the OAG [8], this study desired to use actual flight data, which, in addition to containing information about the origin, destination, and

time of flight, would also provide position information about the aircraft during flight. As a result, flight data from the Aircraft Situational Display to Industry (ASDI) feed was used. The ASDI feed is compiled by the Volpe center from the FAA's Enhanced Traffic Management System (ETMS) and made available to vendors, who can then pass the data on to other interested parties. ETMS data is used by the FAA to monitor and control air traffic flow. The ETMS system includes information about the aircraft during flight, weather information, as well as various tools for monitoring and predicting demand, congestion, and other states of the system. Data regarding aircraft during flight includes flight plan and actual flight path data, which is updated every minute. This data is assembled from the Official Airline Guide (OAG), flight messages from airline flight data systems, and National Airspace System (NAS) messages from the Automated Radar Track System (ARTS). [9]. The ASDI server receives raw data from ETMS, which contains the above mentioned data, as well as TO and RT messages, both described in Table 3, generated by ETMS. The received data is then filtered to remove sensitive data such as information about military flights. The specific rules for filtering the data can be seen in Appendix A. The final ASDI data stream contains 10 message types, which are listed and explained in Table 3. [10]. For the purpose of this research, archived ASDI data was obtained from the Air Traffic Airspace (ATA) Laboratory. The data was obtained in the form of 10 data tables, where each table contains a specific grouping of ASDI messages, retrieved from the Laboratory's ASDI database. From the 10 available tables, this study used the Flight and the Route tables, which contain the desired variables. The list of variables extracted for the purpose of this study can be seen in Figure 5.

This study used ASDI data for one Thursday in January, between 1998 and 2003. Additional days of data were obtained, but the January data was used because it represented the longest sample of consecutive years. The actual dates of days for which data was used can be seen in Appendix B. Since part of the goals of this research was to analyze the emergence and growth of regional jets, multiple years of data were necessary. Furthermore, each data sample is for the same weekday to eliminate the effect of weekly variations in airline operations. The specific day was chosen based on the identification of clear weather days, which were found by looking at the National Climatic Data Center (NCDC) weather archives [11].

Table 3: ASDI NAS Messages [10]

Message	Description
AF	Flight Plan Amendment
AZ	Arrival Announcement
DZ	Departure Announcement
FZ	Flight Plan
RZ	Cancellation
TZ	Position Update
UZ	Flight Plan Update
RT	Extra Data Calculated by ETMS
TO	ARINC Oceanic Flight Reports
HB	Proof of Connection Signal

In order to understand the patterns observed using the ASDI data, Form 41 data was used to study and compare the cost structure of regional jets and other aircraft. Form 41 data includes balance sheet and income statement information from all US airlines that

are required to file with the US Department of Transportation’s Research and Special Projects Administration. This includes all airlines with annual operating revenues of \$20 million or more, and includes all major and some regional airlines. The specific information used for this study included the aircraft operating expenses grouped by aircraft type. [12].

2.3 Data Processing

To effectively use the ASDI data it needed to be consolidated and formatted in a way that made calculations and plotting possible. The desired format was a text file that could be operated on using python and MatLab, but the data required extensive processing and filtering before this format could be achieved. The resulting file consisted of multiple flight records separated by a space. The format of each flight record can be seen in Figure 5. For the purpose of this discussion the first line of the record will be referred to as the header and the subsequent lines as the updates.

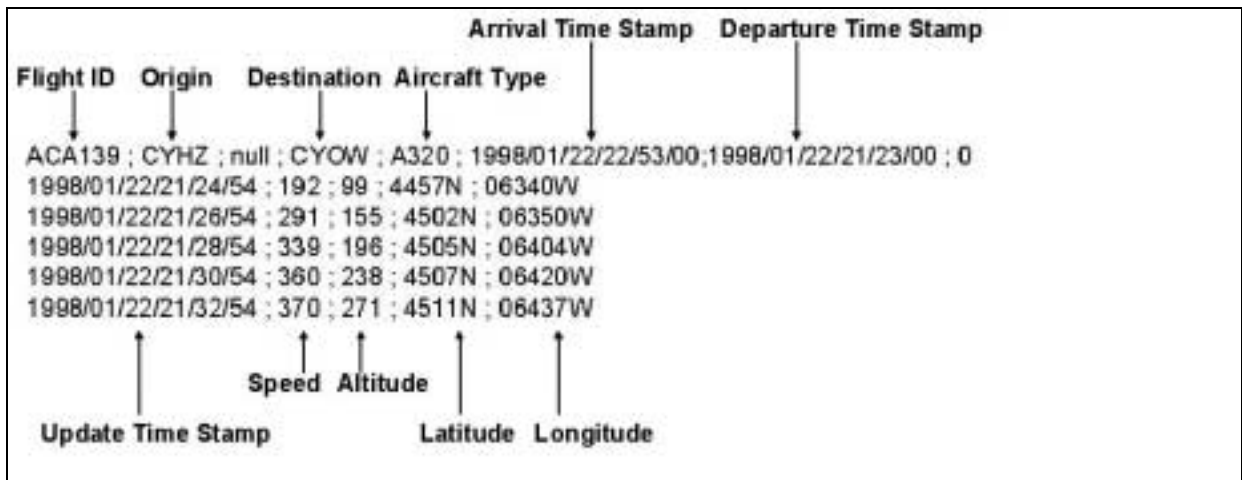


Figure 5: Structure of Processed ASDI Data

The first step in creating a usable version of the data was to consolidate flight messages into a single flight record. Different parts of the flight messages were located in either the Flight or Route files and were matched based on all the fields listed in the header line of the record. It was necessary to use multiple data fields to group flight messages because it is possible for two flights with the same ID and the same aircraft type to be flying at the same time, but in different parts of the country. In consolidating the flight records, flights with missing fields in the header line, as well as flights with fewer than two updates were thrown out. The flights with missing fields in the header line were removed because without this information it is impossible to know if the flight actually flew, what its flight path was, or when it flew. Flights with fewer than two updates were removed because no actual flight lasts only a few minutes, and because if one of the updates is bad it is not possible to determine which. Once the flight messages were assembled into flight records, the next step was to remove flight records that did not make sense. This includes flights where the arrival time was before the departure time and flights where the time of travel did not accurately correspond to the distance of travel. As a result of the above outlined data processing, on average 37% of flights were removed. It is not clear what fraction of the removed flights were actual flights that took place and what fraction was a result of noise in the data. A significant amount of noise can be introduced into the ETMS data because it is based on a real time message stream, and assembled from multiple sources.

The next step in creating a usable data file was to filter out transition and incomplete updates from each record. Transition updates contain information about what the plane is required to do in the future rather than what it is doing now. For example, it may contain

the cruising altitude to which the aircraft will climb. Since these updates do not contain information about the actual behavior of the aircraft they were removed. Updates where the point did not fit in between those surrounding it, as well as updates where speed was zero but altitude was not, and vice versa were counted as incomplete data and also removed. This filtering has no effect on the total number of aircraft that was kept. It does, however, remove updates of specific flights to make the flight trajectory smoother.

Finally, for the purposes of this study the data was broken down into four categories based on aircraft type: the narrow body traditional jets (TJnb), the wide body traditional jets (TJwb), the turboprops (TP), and the regional jets (RJ). The list of aircraft included in each category can be seen in Appendix C. Other aircraft such as general aviation or business jets were not included. As a result, from the data that survived the above outlined process on average about 63% of daily flights were used for analysis.

2.4 Visualization of Traffic Data

To visualize the flight patterns of regional jets and other aircraft, density maps were generated using the ASDI data. The technique for making density maps was based on the algorithms developed by a previous graduate student for a program called Visual Flight [13]. An example of a density map is shown in Figure 6. The plot was generated by dividing the map into a grid and counting the number of flights whose paths intersected each square in the grid. The map was colored based on the number of aircraft that appeared over a specific area during the course of an input time bound. The size of each square in the grid was $1/15^{\text{th}}$ by $1/15^{\text{th}}$ of a latitude longitude increment. It should be noted that if the granularity of the grid is changed, the resulting density values will be altered. This resolution was limited by the computational capability of MatLab.

However, for analyzing large scale patterns over the entire US, this resolution is sufficient. Furthermore, if more accurate resolution is required it can be achieved provided that the data set analyzed is smaller than the one containing 24 hours of flights over the entire US. This can be accomplished by limiting the geographical area, or the time bound studied.

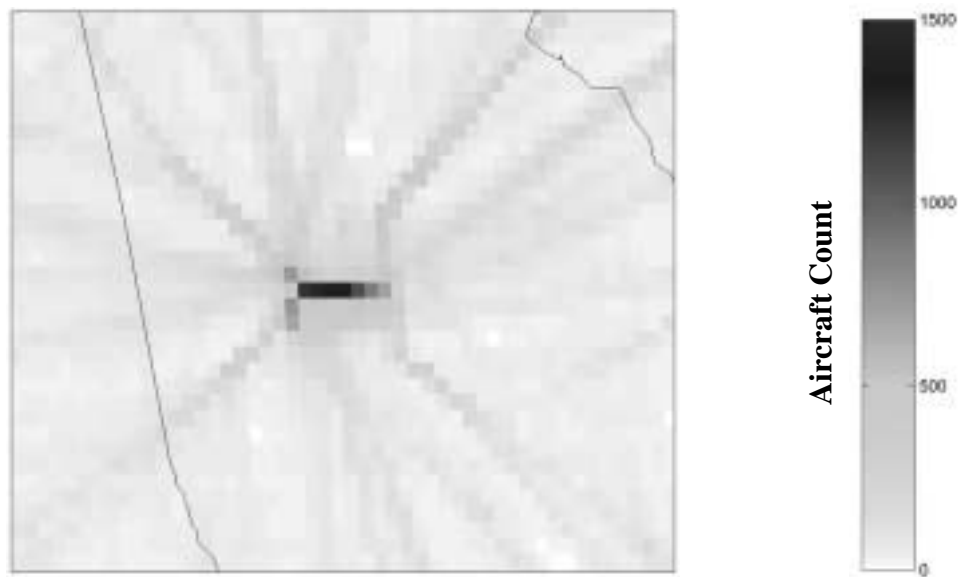
The top limit on the map scale does not represent the highest density of aircraft, rather the scale ends at 100; this was done to create a map with a good contrast between areas of different density. For comparison, a map where the limit of the scale is equal to the highest value of density can be seen in Figure 7. It can be seen from the figure that this scale obscures most of the density differences because very few areas have densities at the high end of the spectrum. In fact, the only places where the density reaches close to the maximum occur almost directly over large airports. An example of such an area can be seen in Figure 8 which shows a close up view of the Atlanta airport.



Figure 6: Density Map of 24 Hours of Flights in January 2003: Limited Scale



Figure 7: Density Map of 24 Hours of Flights in January 2003: Unlimited Scale



**Figure 8: Density Map Close up of 24 Hours of Flights at Atlanta in January 2003:
Unlimited Scale**

3 Operating Patterns of Regional Jet, Traditional Jet, and Turboprops

3.1 Regional Jet Growth and Operating Patterns

As mentioned in the introduction, there has been a significant increase in the number of regional jets in the US. However, in addition to looking at the increase in the number of aircraft, it is also useful to analyze the growth in the number of flights, as well as where in the US those flights cluster. Figures 9 through 14 show the growth in the density of regional jet flights over the US. It can be seen from Figure 9 that in 1998 most of the regional jet flights clustered closely around large airports, such as DFW, ATL, CVG, SLC, LAX, DEN, and SFO. This clustering suggests that the jets were being used for hub feeder operations. Figure 10 shows that in 1999 the densities increased, but the patterns remained very similar. As can be seen from Figure 11, the growth in the regional jet density continued between 1999 and 2000. In particular, a large growth can be seen in the northeast part of the country, and in places like IAH and ORD. Figures 12 through 14 show that between 2001 and 2003, the densities increased significantly all over the US, resulting in a dense covering of regional jet flights over the eastern half of the country. Furthermore, the highest densities can be observed at many of the major airports in the country. In addition, a change in the flight distances can also be observed. There are still flights clustered around hubs, but the distances that these aircraft are flying around the hubs have increased. Close observation of SLC between 1998 and 2003 shows a good example of this change. A map of the location of all the major airports can

be seen in Figure 15. The full names of all the airports can be found in the Abbreviations section at the start of this document.



Figure 9: January 1998 Regional Jet Density Map



Figure 10: January 1999 Regional Jet Density Map



Figure 11: January 2000 Regional Jet Density Map



Figure 12: January 2001 Regional Jet Density Map



Figure 13: January 2002 Regional Jet Density Map



Figure 14: January 2003 Regional Jet Density Map

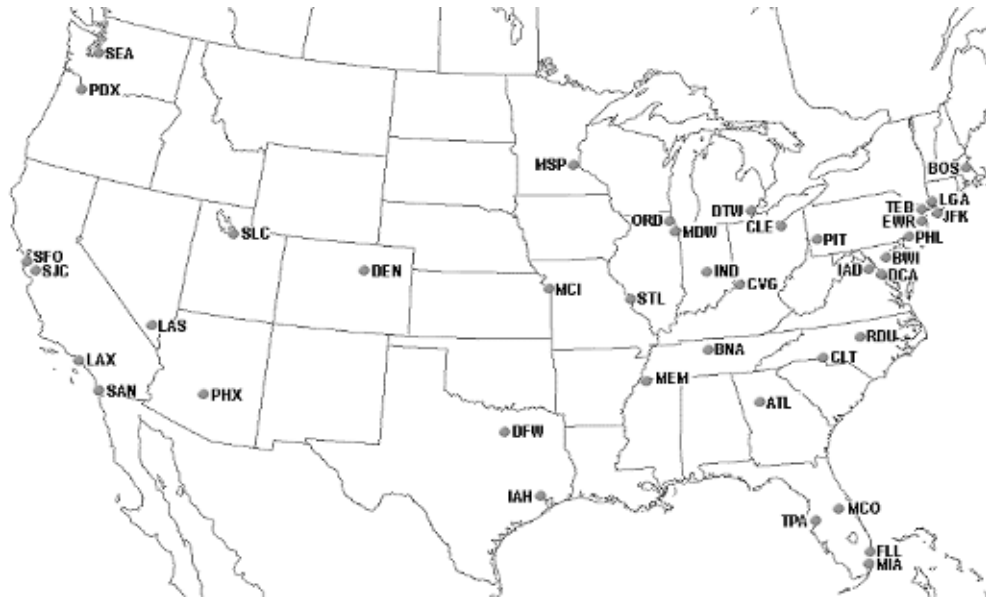


Figure 15: FAA Map of Major Airports in the USA [14]

3.2 Regional Jet Operating Patterns Compared to Other Aircraft Types

The previous section showed the growth and high level development of regional jet pattern between 1998 and 2003. However, it is also important to understand where the regional jet patterns fit as compared to other aircraft types. Figure 16 shows how the 2003 regional jet patterns compare to those of narrow body traditional jets, wide body traditional jets, and turboprops. As was mentioned above regional jets have dense operations in the eastern part of the country and flew increasingly longer stage lengths between 1998 and 2003. In comparison, Figure 16 shows that in 2003 turboprops flew fewer flights than regional jets, but like regional jets showed the highest densities in the north east. It can also be seen that the turboprop operations clustered around major airports, and exhibited relatively short stage lengths. A clear example of this clustering

can be seen at DFW. Narrow body jets have the largest number of flights, showing a high density over all of the US, but like regional jets and turboprops show the largest concentration of flights in the north east and near major airports. It can also be seen that narrow body jets fly longer routes than either regional jets or turboprops. These routes include many transcontinental flights and some international flights. Similarly to narrow body jets, wide body traditional jets fly long stage lengths, with some transcontinental flights and a significant number of international flights. Unlike the previous three categories of aircraft, wide body jets do not exhibit the highest densities in the north east, but show a corridor of dense flights between California on the west cost and the New York region in the east cost.

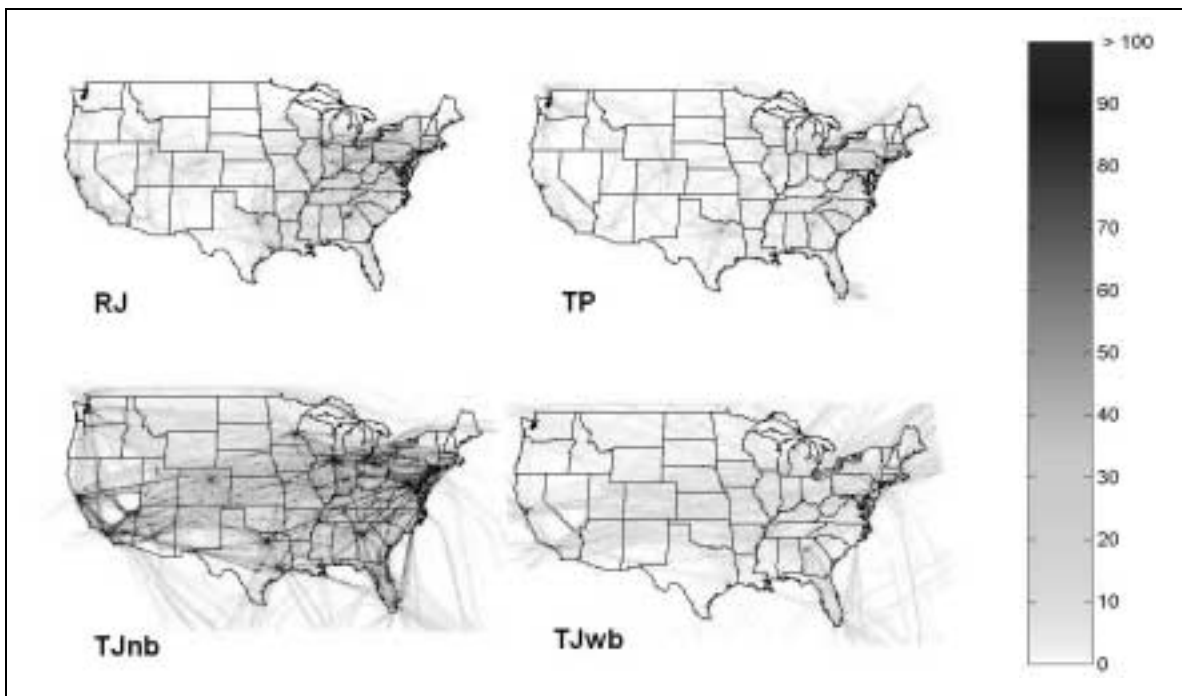


Figure 16: January 2003 Density Maps

3.3 Stage Length Evolution

In order to better understand the observed changes in regional jet operating patterns an analysis of the evolution of stage length was conducted. A specific case of this evolution can be seen by looking at a route map of DFW in 1998 and 2003, shown in Figure 17. The plot shows the catchment basin created around DFW by regional jets, turboprops, and narrow body jets. The catchment basin was defined as the radius within which 95% of all flights from DFW fit. It can be seen from Figure 17 that in 1998 regional jets and turboprops both covered about the same distances away from DFW, with the turboprops having a slightly longer range. The figure also shows that, by 2003, regional jets provided service to cities within a radius of 868 nautical miles around DFW. This new regional jet pattern increased the catchment basin around DFW by over 500 nautical miles, while the turboprop range increased by only about 30 nautical miles. Regional jets evolved from flying the same ranges as the turboprops, to flying ranges in between the turboprops and the narrow body jets, effectively increasing the amount of traffic into DFW. Appendix E contains further examples of airports where regional jets have increased the catchment basin.

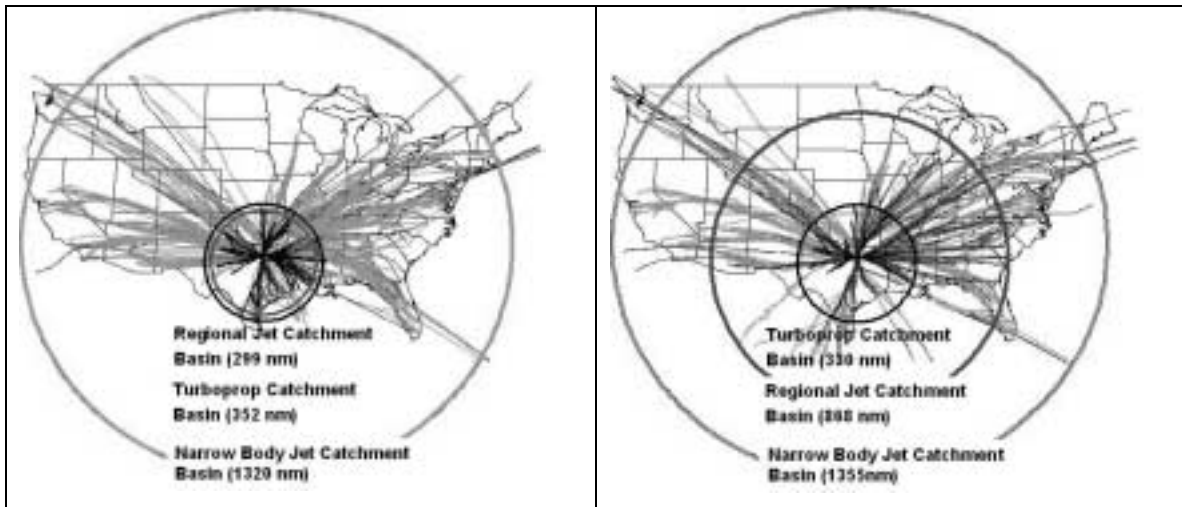


Figure 17: January 1998 and 2003 Departures from DFW

In order to understand the overall change in the stage length flown by regional jet compared to other aircraft types, a histogram of the stage length distribution for each aircraft category was created for January 1998 and January 2003. These histograms show data for flights over the entire US, and not just from one city as in the example above. The histograms are normalized by the total number of aircraft in each category so that the relative shapes of the distributions are not distorted.

Figure 18 shows that in 1998 the regional jet and turboprop distributions were very similar as can be seen from the way the two curves almost overlap. The respective peaks of the regional jet and turboprops both occur at about 250 nautical miles, and both distributions exhibit very few flights longer than 400 nautical miles. Figure 19 shows that while the turboprop distribution changed little; by 2003 the percentage of regional jet flights with stage lengths less than 500 nautical miles had decreased, and the percentage with stage lengths greater than 500 nautical miles had grown. This increase resulted in

regional jets flying stage lengths between those of turboprops and narrow body jets.

Appendix D contains the distance histograms for the years between 1998 and 2003.

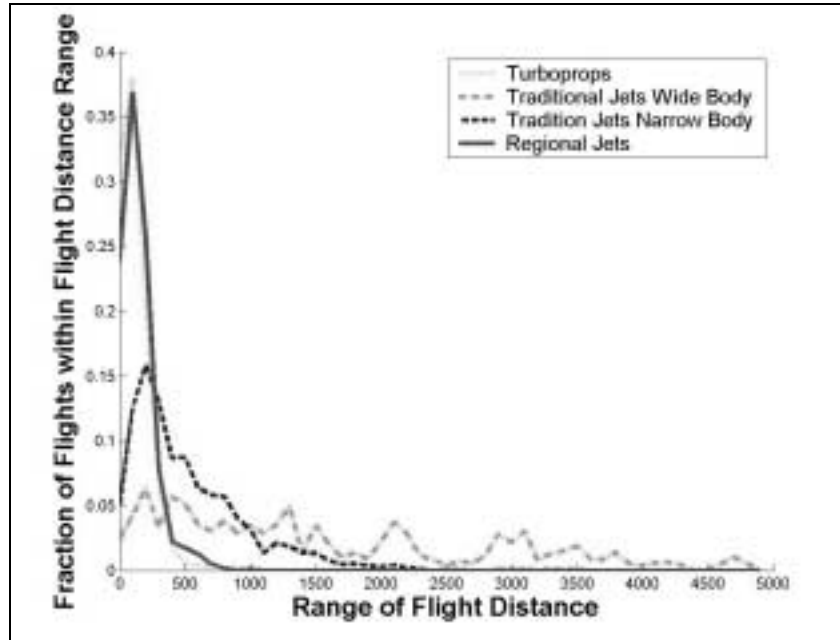


Figure 18: January 1998 Distance Histogram

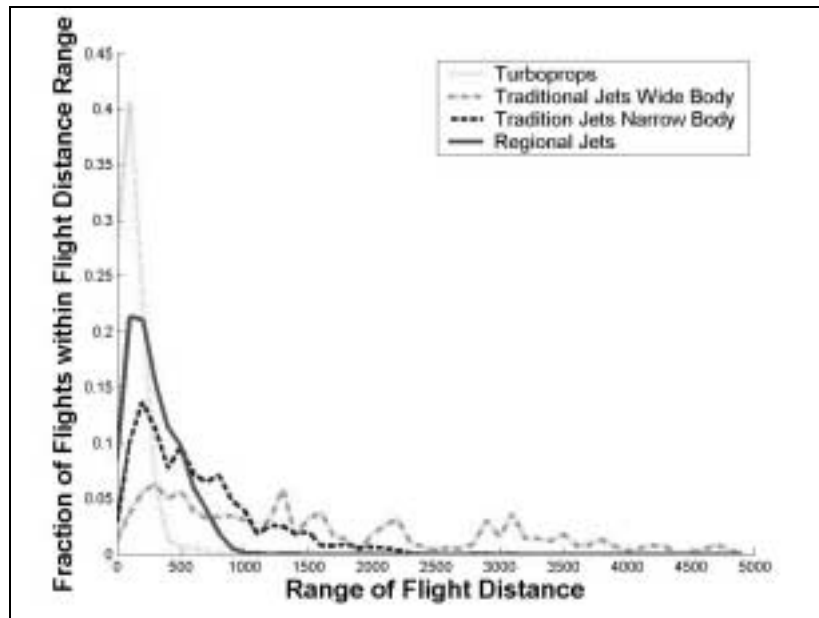


Figure 19: January 2003 Distance Histogram

4 Regional Jet Economics

4.1 Economic Analysis

The goal of this analysis was to understand the cost structure of both regional and traditional jets and to gain insight into the reasons for the observed regional jet patterns. In order to compare the cost of operating a regional jet versus a traditional jet, Form 41 data, between the second quarter of 2002 and 2003 was used. Form 41 data is the mandatory filing of financial data for all large US airlines. This data includes cost and operating information for all airlines with annual revenues over \$20 million. As a result, the number of airlines that fly regional jets and are included in the study was limited, because many of these airlines do not make high enough revenues. In addition, the data was aggregated across airlines according to aircraft type. The aircraft types and air carriers included in the study, as well as the list of regional carriers not included in the study, are shown in Table 4.

Table 4: Aircraft and Carriers Included in the Economic Analysis

Aircraft	Carriers Included in Analysis
B737	Aloha, Alaska, American, America West, Continental, Delta, Frontier, Northwest, Southwest, United
B757	American, Comair, Continental, Delta, Northwest, United, USAirways
A319	America West, Frontier, Northwest, United, USAirways
A320	America West, Jet Blue, Northwest, United, USAirways
CRJ2	Air Wisconsin, Atlantic Southeast, Comair
CRJ7	American Eagle, Atlantic Southeast, Comair, Horizon
E135	American Eagle
E140	American Eagle
E145	American Eagle, Trans States
Excluded Regional Carriers: Ameristar, Chautauqua, Express Jet, Horizon, Mesa, Pinnacle, Republic, Sky West, USA Jet	

In order to evaluate the effect on cost as a result of changes in operation patterns, it is useful to first present the baseline data to which other scenarios can be compared. Table 5, shows the baseline data for all aircraft included in the analysis. The variables shown are those used to calculate the costs per ASM and per trip shown later in this chapter.

Table 5: Baseline Regional Jet Operations and Economic Data

Aircraft	Number of Trips	Average Trip Length	ASMs ('000s)	Pilot Cost per Block Hours
B737	2260194	663.4188	198255980	430
B757	598628	1236.488	133443130	547
A319	379018	1094.385	60751749	411
A320	325124	930.9654	37057260	460
CRJ2	285650	459.0012	6230958	287
CRJ7	68209	542.2846	2592234	215
E135	86333	351.4938	1122784	181
E140	92788	386.0613	1576162	169
E145	157506	353.5711	2784478	187

4.2 Regional Jet Costs

The flight operating costs per ASM for all the aircraft included in the study are shown in Figure 20. The per ASM metric is a good way to look at costs because it directly relates the cost to the product that the airline is selling: a seat to a passenger on a specific route. It can be seen from the figure that the regional aircraft costs per ASM are much higher than those of the narrow body jets. This is due to the fact that regional jets have fewer seats and are generally operated on shorter routes. Given this cost difference, the rapid growth in regional jets may appear somewhat surprising. However, currently many regional jet flights are flown on behalf of a major airline. Major airlines contract with regional airlines to incorporate regional jet flights into their network structure covering the cost of the flight on a “fee-per-departure” basis.

Figure 21 shows the flight operating costs per flight. It can be seen from the figure that the costs of regional jets per flight are significantly lower than those of narrow body jets. Given the “fee-per-departure” structure of many contracts between major and

regional airlines, it can be seen that the regional aircraft flights are less expensive for the major airlines than their own narrow body flights.

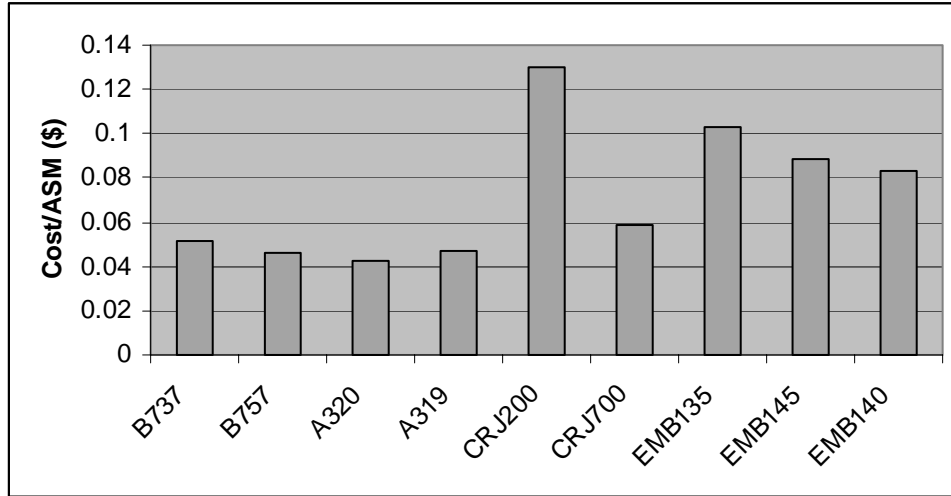


Figure 20: 2002-2003 Flight Operating Costs per ASM

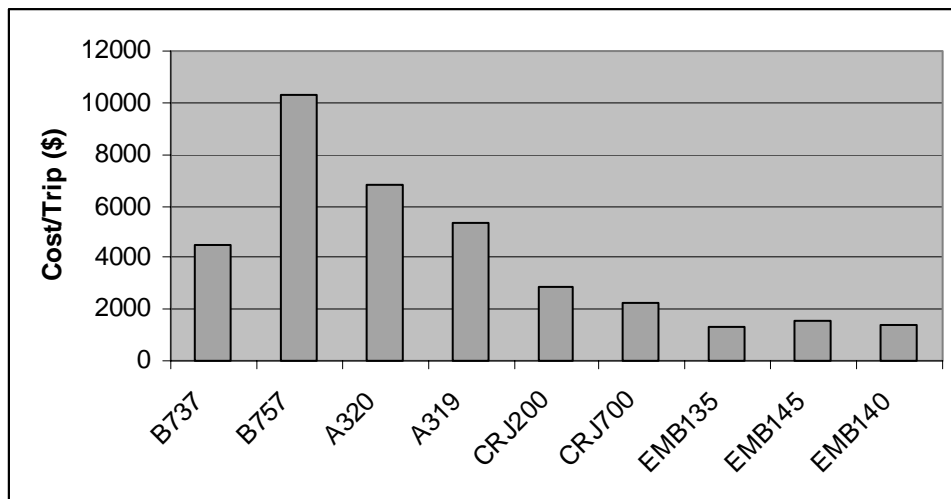


Figure 21: 2002-2003 Flight Operating Costs per Trip

4.2.1 Regional Jet Costs as a Function of Stage Length

While the above analysis provided information about each aircraft type, it did not provide any insight into how the costs of these aircraft would change if they were all used under the same operating conditions. In particular, the data doesn't show how operating costs per ASM and per departure change when flight distances are changed. As a result, the goal of the following analysis was to normalize the effect of stage length and compare the cost of regional and traditional jets if they were to fly the same routes. Changes in stage length were analyzed because, as shown in chapter 3, the stage length of regional jets has increased significantly between 1998 and 2003. If this trend continues, it is valuable to know what the effect on the cost of regional jets will be.

In order to show the effects of changes in stage length on the overall operating cost per ASM and per trip it was assumed that flight operating costs scale linearly with the number of block hours flown. It was also assumed that maintenance costs, which are added to the flight operating costs to make up the total operating costs, scale with the number of take offs. In this analysis, the number of take offs was kept constant and as a result the maintenance costs did not change. While it may have been more accurate to use existing data and model costs using regression, not enough data points were available due to the small number of regional airlines that file Form 41 data. Once the costs could be modeled given changes in the stage length, the next step was to equalize the stage length in order to compare how expensive narrow body and regional jets would be if they were used on the same trips. The chosen stage length was 1000 miles. This number represents the rounded average of the base case narrow body jet stage lengths. The mathematical formulation of this model can be seen in Appendix F.

It can be seen from Figures 22 and 23 that regional jet costs per ASM and per trip both increase over the baseline case, but that the per trip costs increased by a higher percentage. This result indicates that if regional jets are flown on the same distance routes as traditional jet aircraft, the “fee-per-departure” payment structure will no longer make the regional jet a significantly cheaper alternative to a narrow body jet. For example, when the CRJ200 is compared to the B737 it can be seen that when the trip length is increased to 1000 miles, the costs per trip of the two aircraft become very similar. Furthermore, the costs per ASM will still remain much higher than those for traditional jets making regional jets a less economical choice.

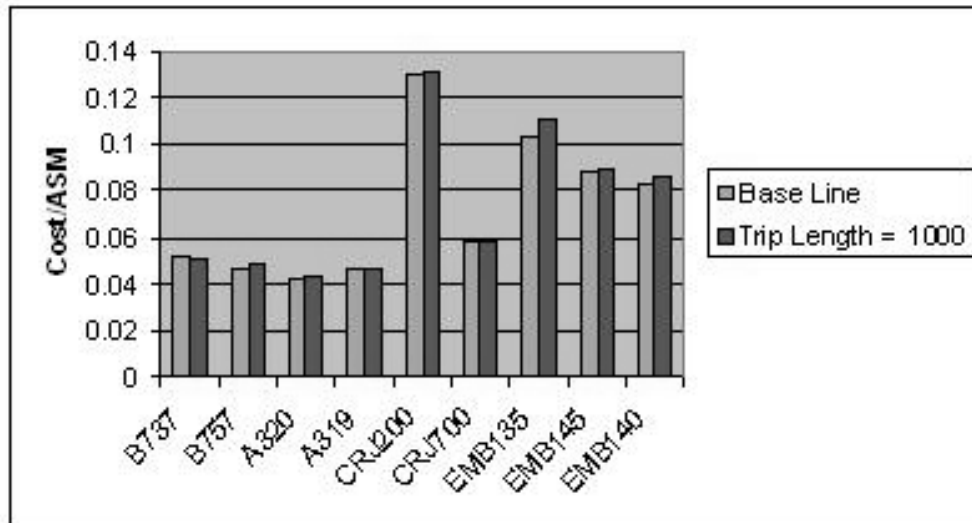


Figure 22: Comparison of Operating Cost per ASM with and without a change to Stage Length

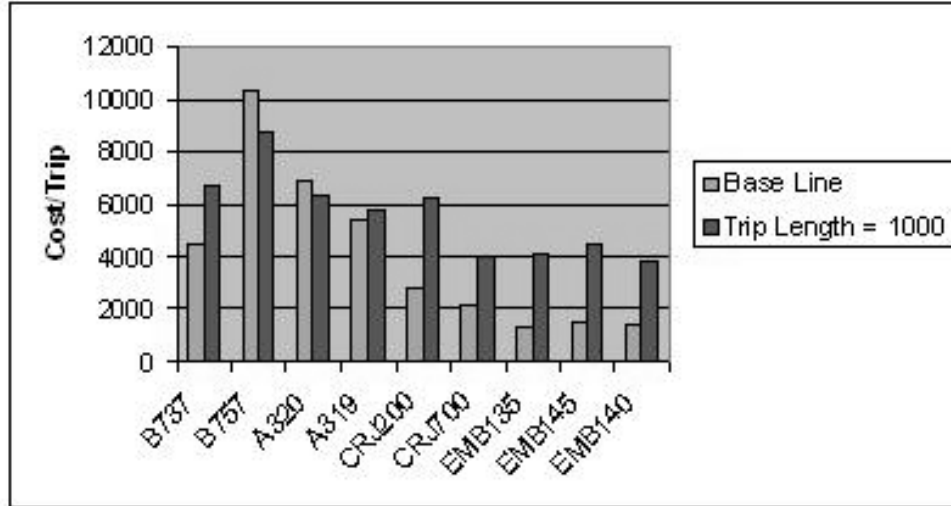


Figure 23: Comparison of Operating Cost per Trip with and without a change to Stage Length

4.2.2 Operating Cost as a Function of Pilot Cost

The decision to investigate the effect of changes in pilot costs was made because the lower crew costs of regional jets are often cited as the reason why regional jets have been growing rapidly in the US [15]. As a result, it is valuable to know how regional jet costs compare to narrow body jet costs when crew costs between the two aircraft types are equalized. In order to show the effects of changes in crew costs on the overall operating cost per ASM and per trip it was assumed that pilots are paid per block hour of flight. The chosen pilot cost per block hour was \$450, which is the average of the values for the narrow body jets, rounded to the nearest 50.

Figures 24 and 25 show that regional jet costs increase in both cases, but the differences are not significant enough to make regional jets any more or less economical than traditional jets. Their cost per ASM is still significantly higher and the cost per trip

is still significantly lower than the cost of traditional jets. This indicates that the lower crew costs of regional jet operations are not the reason that regional jets are considered to be less expensive. Rather, as shown in the previous section the “fee-per-departure” is what makes the regional jet an affordable alternative to narrow body jets.

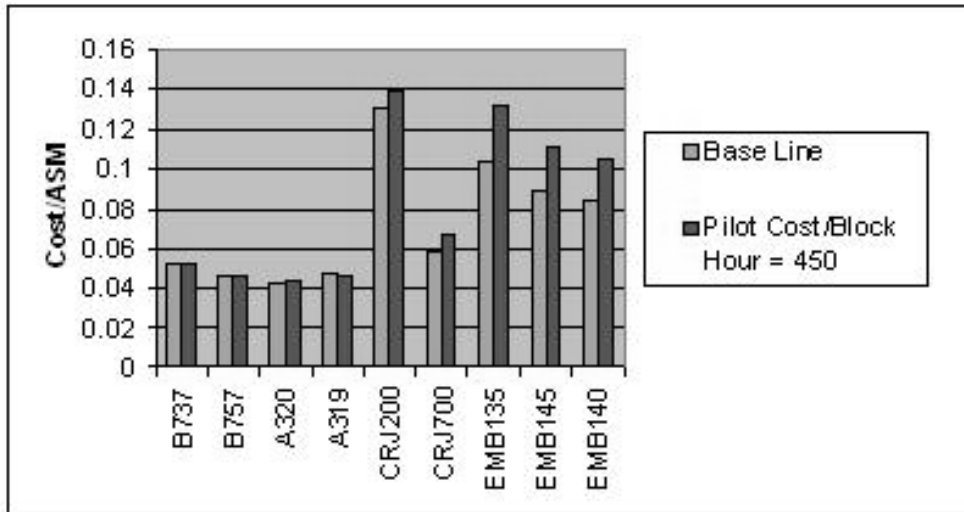


Figure 24: Comparison of Operating Cost per ASM with and without a change to Pilot Costs

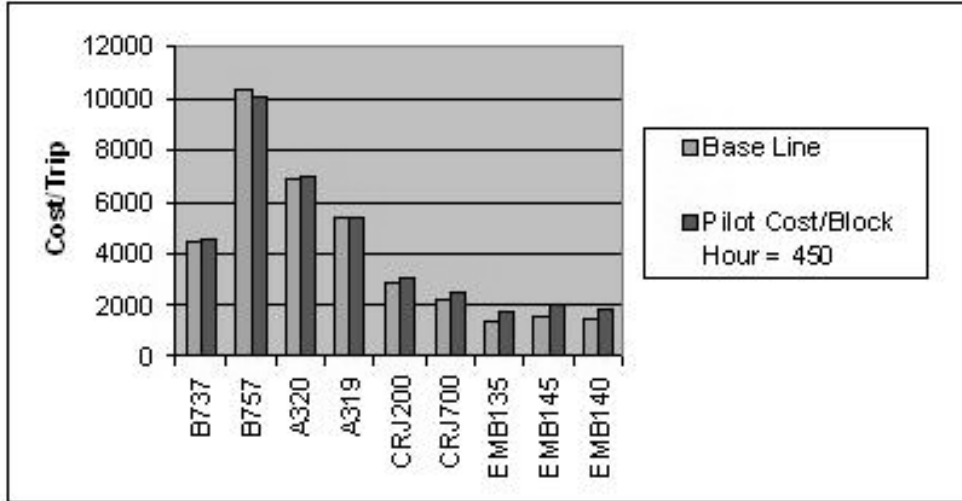


Figure 25: Comparison of Operating Cost per Trip with and without a change to Pilot Costs

4.3 Ownership Costs

In addition to calculating how the operating costs changed with pilot costs and trip length, the change in costs when ownership expenses are taken into account is also of interest because this cost often accounts for a large percentage of the overall aircraft cost. However, From 41 data does not provide ownership cost information per aircraft type. As a result, in order to calculate the ownership cost for each aircraft type a list price for each aircraft was approximated based on a few published values [16] [17], a loan time of 20 years and an interest rate of 10% were assumed. The list prices for each aircraft can be seen in Table 6. It was also assumed that all the aircraft are owned not leased, or that the yearly cost of the lease is equivalent to the yearly amortized ownership cost under the conditions described above.

Table 6: List Prices by Aircraft Type

Aircraft Type	List Price
B737	50,000,000
B757	75,000,000
A320	65,000,000
A319	50,000,000
CRJ2	40,000,000
CRJ7	40,000,000
E135	40,000,000
E140	40,000,000
E145	40,000,000

Once the ownership costs were calculated the total cost per ASM and per trip was found. Figures 26 and 27 show the comparison of costs per ASM and per trip for both the baseline case and the baseline case with the addition of ownership costs. It can be seen from Figure 26, that the cost per ASM of regional jets increases significantly when ownership costs are added. In fact, the figure shows that the cost per ASM of regional jets and narrow body jets is about equal if the ownership costs are included for the narrow body jets and not included for the regional jets. This indicates that the regional aircraft would have to be sold at a significant discount in order to equalize the cost per ASM of regional and narrow body jets. While the sale prices of aircraft are not known, there is evidence that both Bombardier and Embraer provide incentives in the form of low interest rates to make their regional jets more affordable: According to a dispute brought before the World Trade Organization (WTO), Bombardier and Embraer have both at different times complained that their sales are being undermined by the ability of the other company to offer substantially lower interest rates as a result of government support

[18]. In contrast, when looking at the cost per trip the regional aircraft remain significantly less expensive than traditional jets.

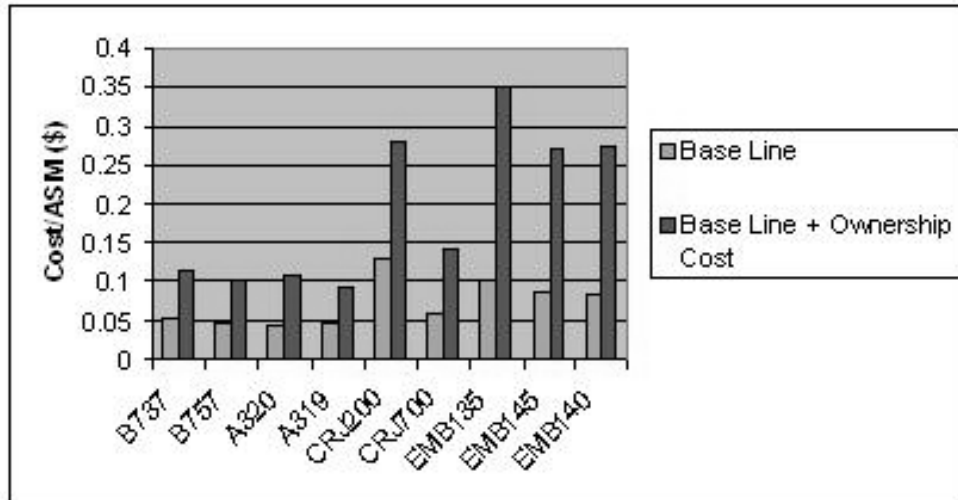


Figure 26: Comparison of Operating Cost per ASM with and without Ownership Costs

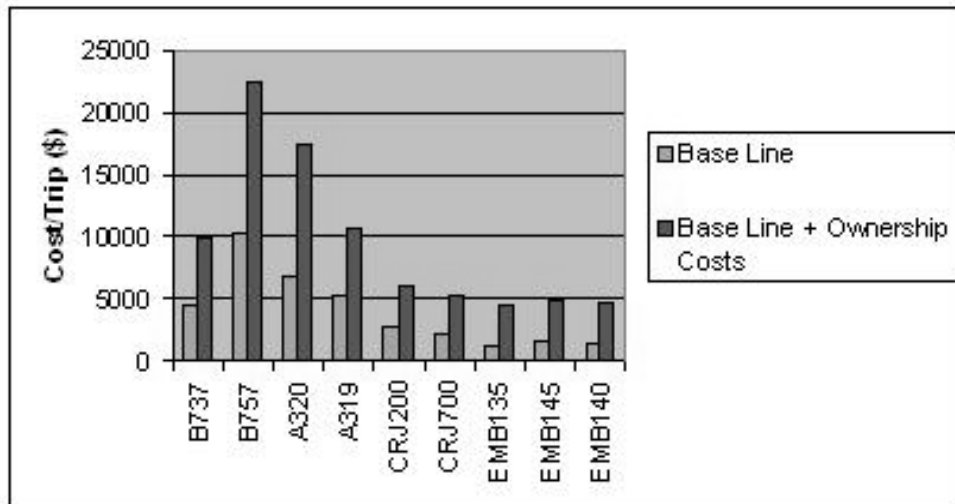


Figure 27: Comparison of Operating Cost per Trip with and without Ownership Costs

5 Understanding Regional Jet Growth and Patterns

5.1 Reasons for Regional Jet Growth

When regional jets were first introduced, they provided service similar to turboprops, and in many cases replaced turboprop aircraft and flights. Part of the reason for this replacement was the public perception, most likely caused by the fact that turboprops fly at lower and more turbulent altitudes, that turboprops are less safe than jets. However, soon after their introduction, regional jets began to fly longer distances and serve new markets. Figure 28 shows the changes caused by regional jet routes between 1992 and 2001, as well as between the start and end of 2002. As can be seen, while regional jets have supplemented and replaced both turboprop and traditional jet routes their primary function has been to create new routes.

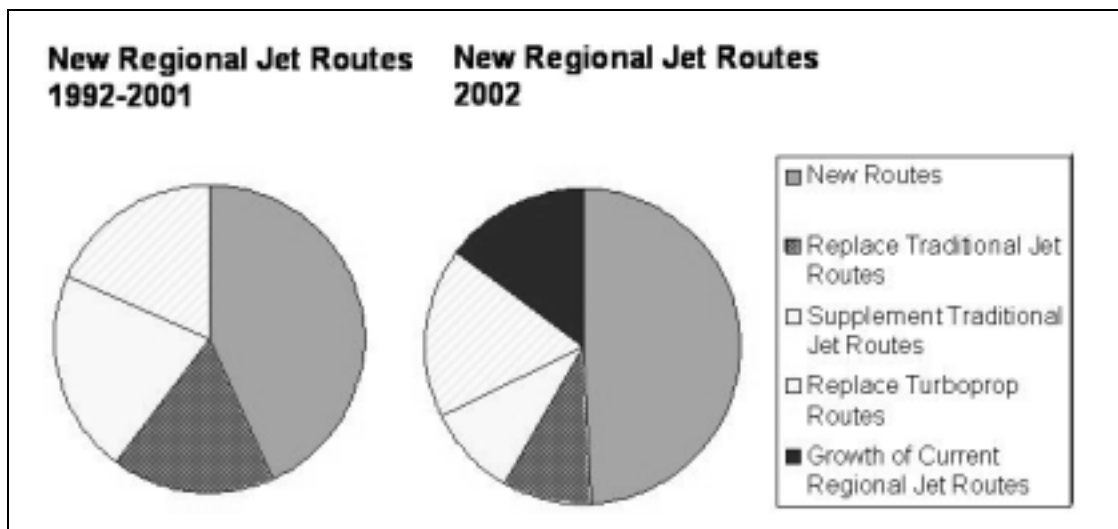


Figure 28: Change in Routes between 1998 and 2003 [19]

Regional jets have been successful in creating new routes because their smaller size means they can serve routes that do not have enough demand to warrant a traditional jet. While it was shown in the previous section that regional jets are more expensive per seat, because of yield management, having the right number of seats is more profitable than having more seats to spread the cost among. Yield management allows an airline to maximize yield by selling as many high priced tickets as possible. If an aircraft is correctly sized to the market it can be filled with high paying passengers and result in higher revenues. Passengers will compete for the available seats, and those willing to pay more will buy the tickets. However, if an aircraft is too large there are always available seats. As a result, the airline has to discount the ticket prices in order to fill enough seats to cover their costs.

The addition of regional jets allowed major airlines to serve small, but profitable cities, which had been too far to efficiently serve with a turboprop and did not have enough demand to serve with a traditional jets. In addition, to airlines could expand and support their hub operations by using regional jets to feed passengers into the hub [20]. This utilization can be observed in Figure 29. The figure shows that rather than providing point to point service, over 90% of regional jet flights start or terminate at a hub or major airport. The list of airports considered as hubs for the purpose of this study can be seen in Appendix G.

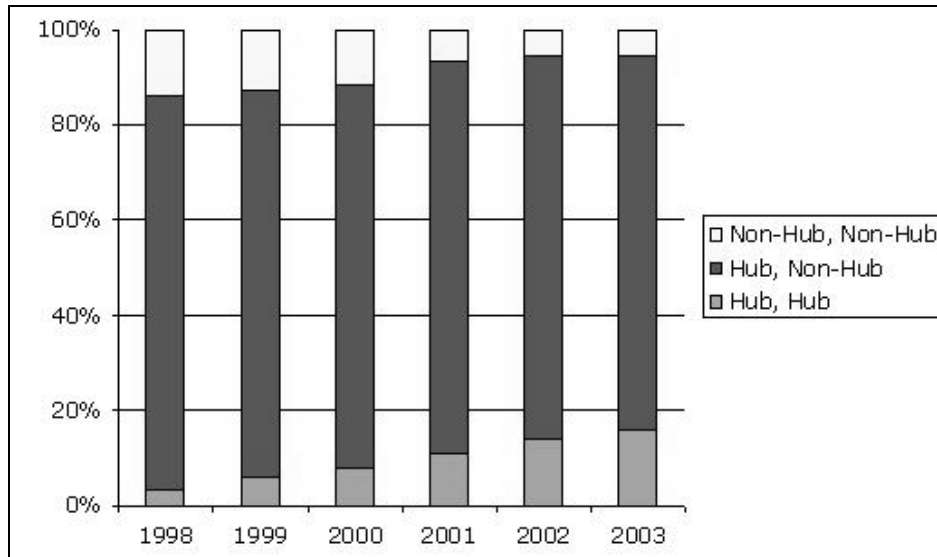


Figure 29: Percentage of Regional Jet Flights Providing Service between Hub and Non-hub Airports

While major airlines have benefited from the use of regional jets, as mentioned in the previous chapter, most do not directly own any regional aircraft. Instead, major airlines incorporate regional jet flights into their operations by having wholly-owned subsidiaries or by code sharing with small regional carriers. An example of a wholly owned subsidiary is American Eagle, where American is the owner company. Table 7 shows the list of regional jets used by regional carriers and the major airlines that they partner with. This structure ensures that regional jet crews are on a different pay scale and allows major airlines to pay the regional carriers on a per departure basis.

Table 7: US Regional Carrier and Code Share Partners [18]

Aircraft Type	Regional Carrier	Code Share Partners/Carriers
E135	American Eagle Continental Express Republic	American Continental America West, Delta, US Airways
E145	American Eagle Continental Express Mesa Republic Trans State	American Continental America West, Frontier, US Airways America West, Delta, USAirways America, US Airways
CRJ1	Comair Sky West	Delta Delta, United
CRJ2	Air Wisconsin Atlantic Southeast Mesa Sky West	Air Tran, United Delta America West, Frontier, US Airways Delta, United
CRJ7	American Eagle Atlantic Southeast Comair Horizon Mesa	American Delta Delta Alaska, Northwest America West, Frontier, US Airways
BA46	Air Wisconsin Mesaba	Air Tran, United Northwest

5.2 Constraints on Regional Jet Growth

The growth of regional jets, while rapid, would most likely have been faster if not for the restrictions placed on major airlines by scope clause agreements. Scope clauses are

part of labor contracts between airlines and airline pilots. They limit the number and size of regional jets that an airline can own, as well as cities or routes where the airlines can operate regional aircraft. Pilots working at major airlines are thwarting the growth of regional jets because they see them as a direct threat to their jobs. As shown earlier regional jets have created new routes, but have also replaced or supplemented traditional jet routes, taking jobs away from traditional jet pilots. In addition, traditional jet pilots can assume that they would have flown on some of the new routes created by incoming regional jets [19]. Finally, since most major airlines pay pilots based on the size of the aircraft they fly, the popularity of new smaller aircraft threatens not only their jobs, but their salaries as well. As a result, major airline pilots have fought back with scope clauses.

An example of a simple scope clause agreement can be seen at Continental Airlines. The airline is allowed to operate any number of regional jets with fewer than 59 seats, but cannot own larger regional aircraft. Table 8 shows the fleet, as of December 2003, of Continental Express, now known as Express Jet, which is the regional partner for Continental Airlines [21]. It can be seen that the airline owns only regional jets with 50 seats or less rather than 59 seats or less. The reason for this difference is that there are no regional jets available with over 50, but fewer than 59 seats; the closest model after 50 seats has 70 seats.

Table 8: Continental Express RJ Fleet as of December 2003

Aircraft Type	Number of Aircraft	Number of Seats	Restrictions
ERJ 135	30	37	No restrictions on aircraft with under 59 seats
ERJ 145	140	50	
ERJ 145 XR	54	50	

As a result of the post 9/11 economic downturn many airlines have been facing financial problems and renegotiating their existing pilot contracts. As a result, the effect of scope clauses is likely to change. The changes in the scope clauses are complicated and it is unclear if they will result in an increase in regional jet operations. However, there is evidence that airlines are negotiating contract that will allow them to operate regional aircraft with a higher number of seats. Between the Fall of 2001 and 2003 United Airlines and USAirways both negotiated contracts that allow them to fly aircraft with additional 20 and 7 seats respectively. A summary of scope clause restrictions for both dates is provided by the Regional Air Service Initiative (RASI) and can be seen in Appendix H.

5.3 The Future of Regional Jets

The future growth of regional jets depends on many factors, and as a result it is uncertain. However, it is known that in the next few years, both US Airways and Jet Blue will be receiving a large number of regional jets, which means that some growth in registrations will continue for at least the next few years. Figure 30 shows the past growth of regional jets and arrows depicting the uncertainty of future growth. Many airlines are currently in financial difficulty and it is unclear what the future successful

airline business model will look like, if it will include regional jets, and what the labor and code share arrangements will be like. It is possible that at some point the “fee-per-departure” structure will change, making the use of regional jets less affordable. It is also possible that the partnerships between regional and major airlines will be disbanded. Atlantic Southeast has been a regional partner of United, but has announced that it will transition to operating independently [22]. Whether or not the airline will be successful may provide insight into the viability of regional jet economics.

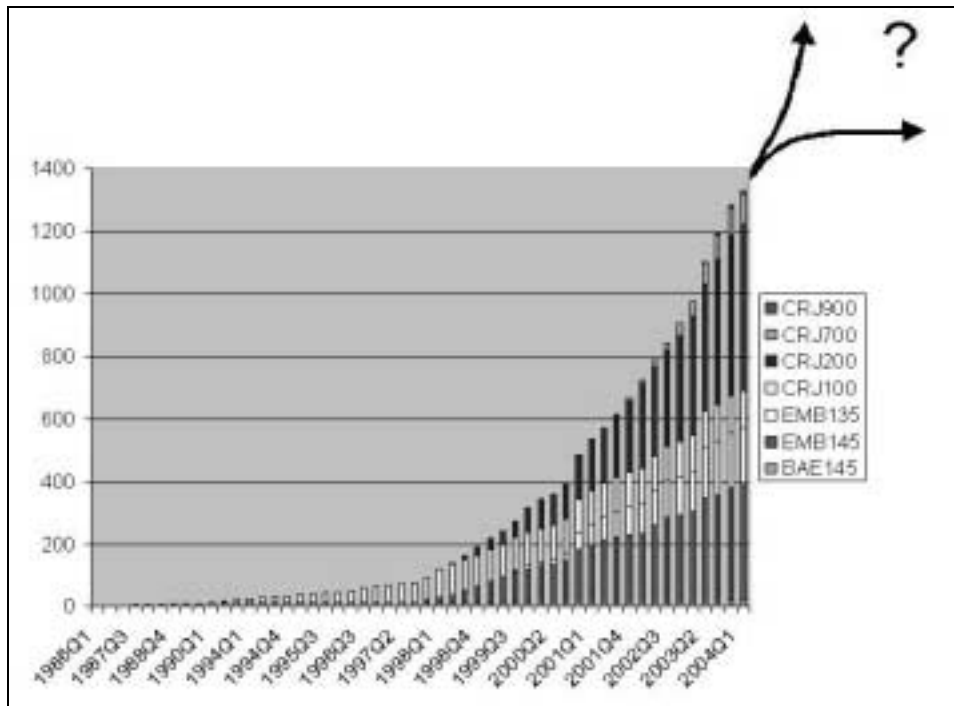


Figure 30: Past and Projected Growth of Regional Jets [21]

While many of the major airlines are currently struggling financially, it is known that at some point in the future the economic situation will improve, and as a result, demand and capacity will grow as well. It is unclear whether, under increased demand, regional

jets will be able to provide the necessary amount of capacity, or if they will need to be replaced with narrow body jets or larger regional jets. If regional jets will have to be replaced, it is unclear what they will be used for. One possibility is that they will replace the remaining turboprops in the national fleet.

Currently both Embraer and Bombardier are building larger regional jets, which can be seen in Figure 31. These new airplanes seat between 70 and 110 passengers, which means that the line between regional jets and narrow body traditional jets will blur further. Embraer believes that there is a capacity gap in the market and that the new 70 to 110 seat aircraft will help to fill that gap [23]. This new size of regional jets will further change the composition and performance range of the national fleet, making the future unclear. In addition, it was mentioned in chapter 4 that regional jets are most likely being sold at a discount or with highly favorable financing. If Embraer and Bombardier stop offering deals to stimulate the purchase of regional jets, the operational cost of these aircraft compared with narrow body jets will increase even further.



Figure 31: Examples of an ERJ 190 (98 seats) and CRJ 900 (86 seats)

6 Comparison of Regional Jet, Traditional Jet, and Turboprop Performance

6.1 Performance Study Motivation

In order to understand the implication of regional jet growth on the ATC and ATM systems, an analysis of the performance differences between regional jets and other aircraft was conducted. Possible implications of these differences are further discussed in chapter 7.

6.2 Comparison of Cruise Speeds and Altitudes

The changes in the operational patterns of regional jets resulted in a change in observed regional jet performance. It is important to note that these changes in performance are not a result of increased capabilities of the aircraft, rather as regional jets began to be used less like turboprops their full capabilities could be utilized. The change in regional jet performance can be seen by looking at the change in primary cruise altitudes and cruise speeds flown by the aircraft. The primary cruise altitude was defined as the altitude at which the aircraft flew for the longest consecutive number of updates. Cruise speed is the average speed at the primary altitude. Once again the histograms are normalized to factor out the number of aircraft in each of the four categories.

Figures 32 and 33 show the histograms of the primary cruise altitudes in January 1998 and 2003 respectively; histograms for other dates can be seen in Appendix I. It can be seen that 1998 the regional jet cruise at altitudes most similar to those of the turboprops. However, the regional jet distribution shows a higher percentage of flights

cruising above 150 flight level. In addition the peak of the turboprop distribution is at about 50 flight level, which is significantly lower than the peak of the regional jet distribution that occurs at about 200 flight level. Figure 33 shows that in 2003 the regional jet cruise altitude distribution fits almost exactly in between the turboprop and narrow body distributions. The peaks of the turboprop, regional jets, and narrow body distributions occur at about 150 flight level, 250 flight level, and 350 flight level respectively.

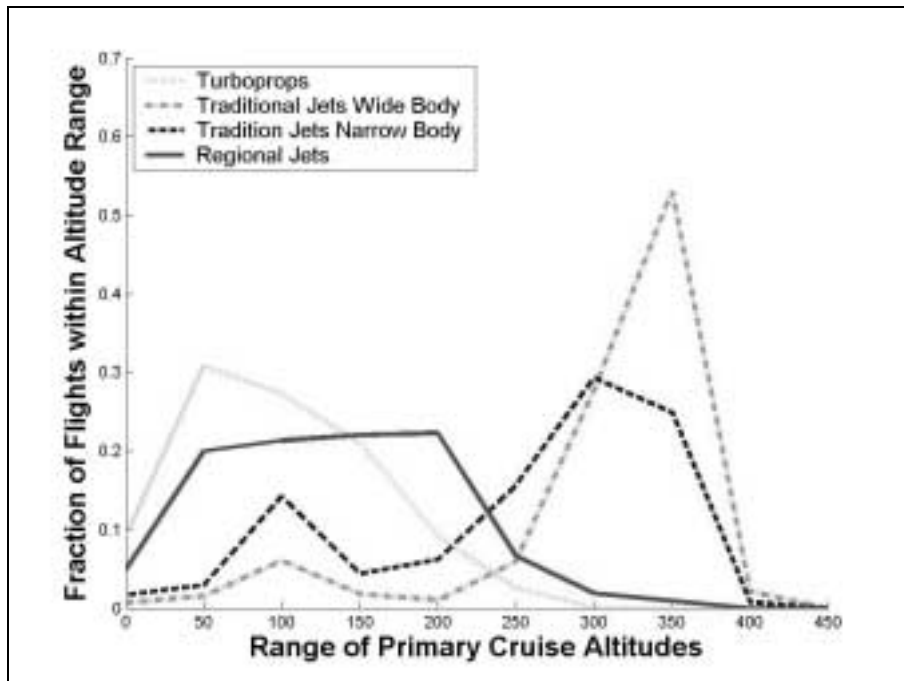


Figure 32: January 1998 Histogram of Primary Cruise Altitudes

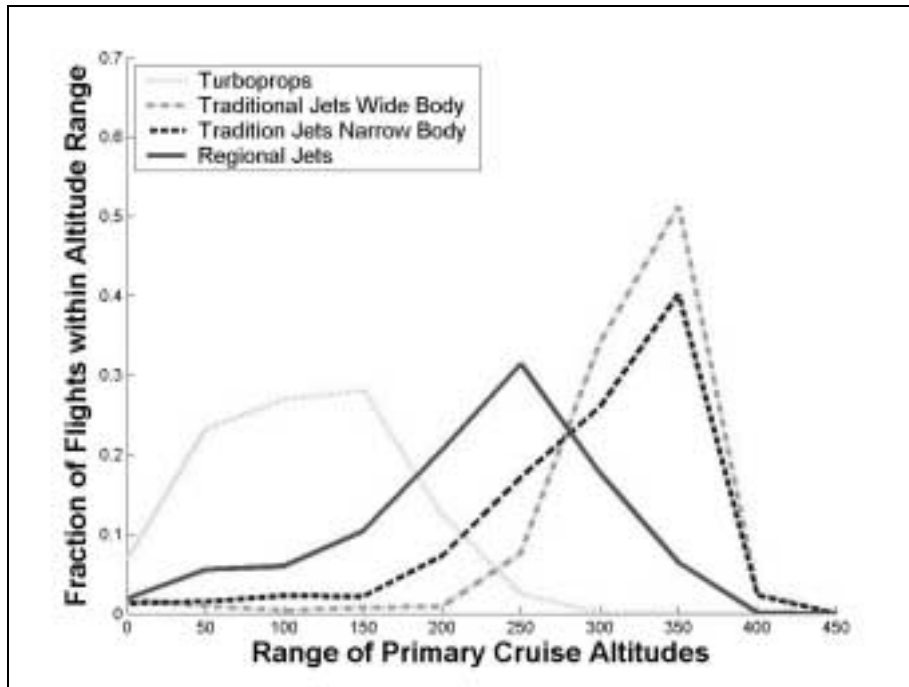


Figure 33: January 2003 Histogram of Primary Cruise Altitudes

Figures 34 and 35 show the cruise speed distribution for all four aircraft categories in 1998 and 2003 respectively. More examples of speed histograms can be found in Appendix J. It can be seen that in 1998 regional jets flew at speeds very similar to those of the turboprops. This is most likely due to the fact that many regional jets shared cruise altitudes with turboprops and as a result had to conform to their speed capabilities. The plot also shows regional jets cruising at speeds between 300 and 500 miles per hour: those are most likely the regional jets sharing cruising altitudes with narrow bodies. Figure 35 shows the speed distributions in 2003. It can be seen that regional jets are now cruising at speeds very similar to the narrow body jets, with both distributions peaking at about 400 miles per hour. Based on the analysis of the cruise altitudes and speeds, it can be seen that while regional jets are capable of cruising at the same speeds and altitudes as narrow body jets, a significant number still fly lower. The most likely explanation for

this is that since regional jets fly shorter distances they are assigned lower cruise altitudes. In this way the aircraft do not have to cross traffic cruising at lower altitudes while they climb up to their cruising flight level and then cross it again when they descend.

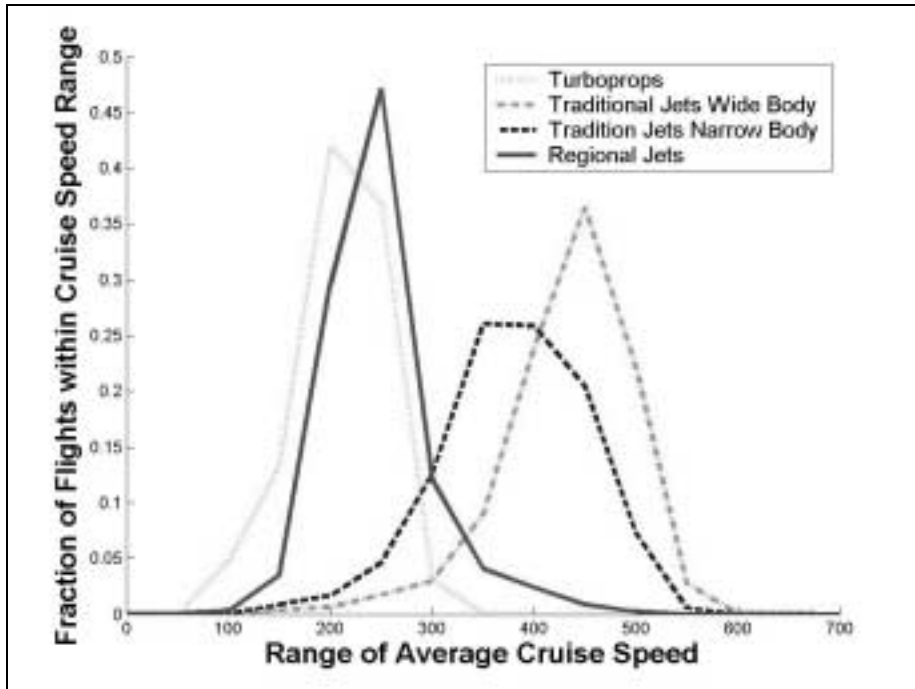


Figure 34: January 1998 Histogram of Average Cruise Speeds

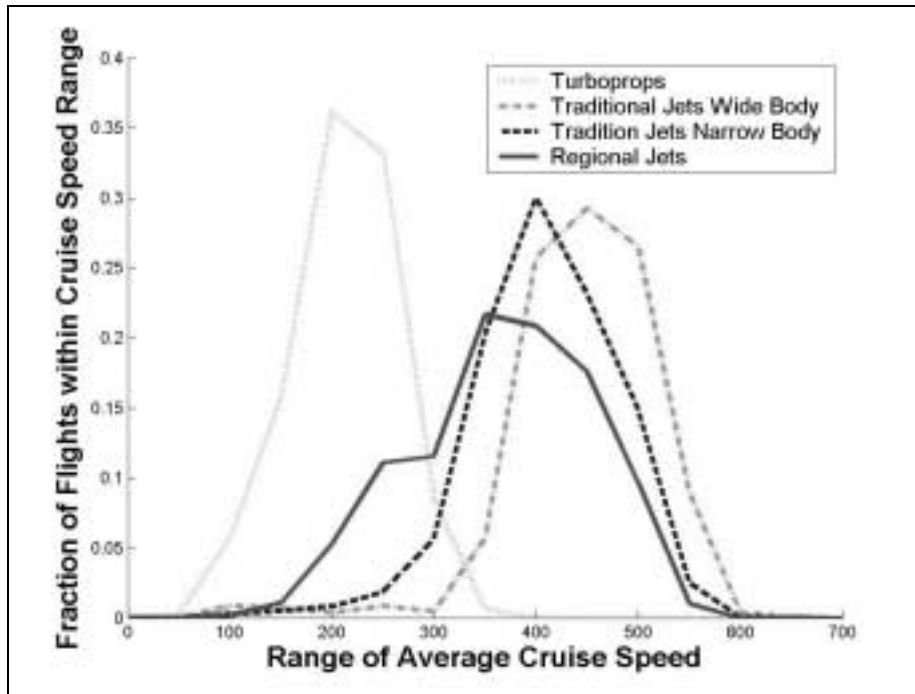


Figure 35: January 2003 Histogram of Average Cruise Speeds

6.3 Comparison of Climb Rates

In addition to the performance during cruise, climb rates were also analyzed. Figures 36 through 39 show the climb rate distributions for the A320, B737, CRJ2, and E145 respectively. More examples can be found in Appendix K. The figures show the climb rates a function of altitude for each aircraft type. The altitudes were grouped every 1000 ft, and the cells in the plot are colored according to the number of aircraft that climbed at a given rate during the 1000 ft increment. It can be seen from the plots that the regional jets climb slower than narrow body jets at all altitudes. Below 10,000 ft the speed of flight is restricted and as a result the climb rate profiles of all the aircraft type are similar. This speed restriction is also the reason for the sharp decrease in climb rates after 10,000 feet, where aircraft are using power to speed up rather to climb. The difference in climb

rates between the regional and narrow body jets is particularly noticeable between 10,000 and 20,000 ft. It is also interesting to point out that at altitudes over 20,000 ft the Embraer regional jets climb faster than the Bombardier jets. This is most likely because the Embraer jets choose climb rate over speed, where the Bombardier jets choose to fly faster and decrease the climb rate. The fact that regional jets climb slower than traditional jets may provide another explanation for why they cruise at lower altitudes. Controllers may level the aircraft sooner to prevent them from slowing down the departing traditional jet traffic.

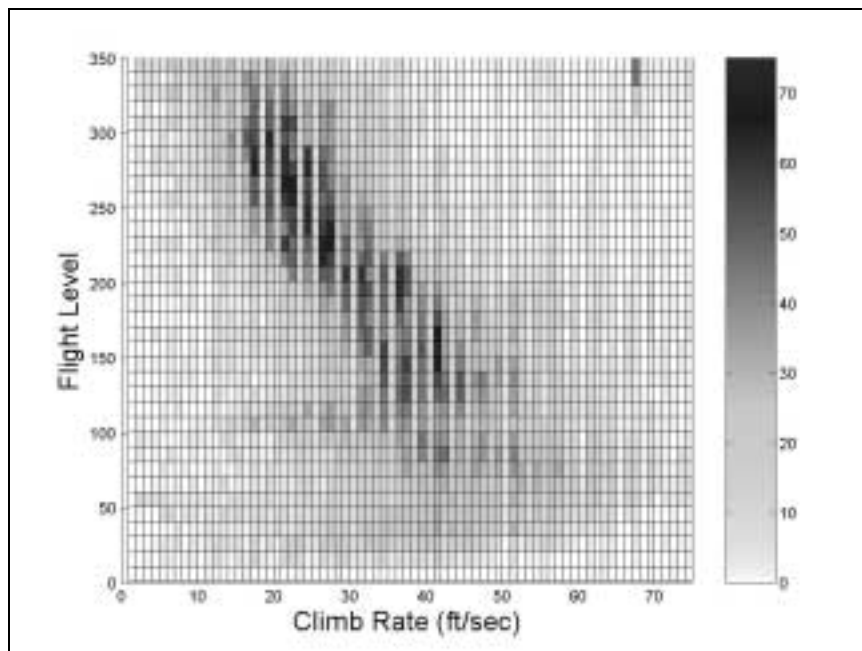


Figure 36: A320 Climb Rate Distribution

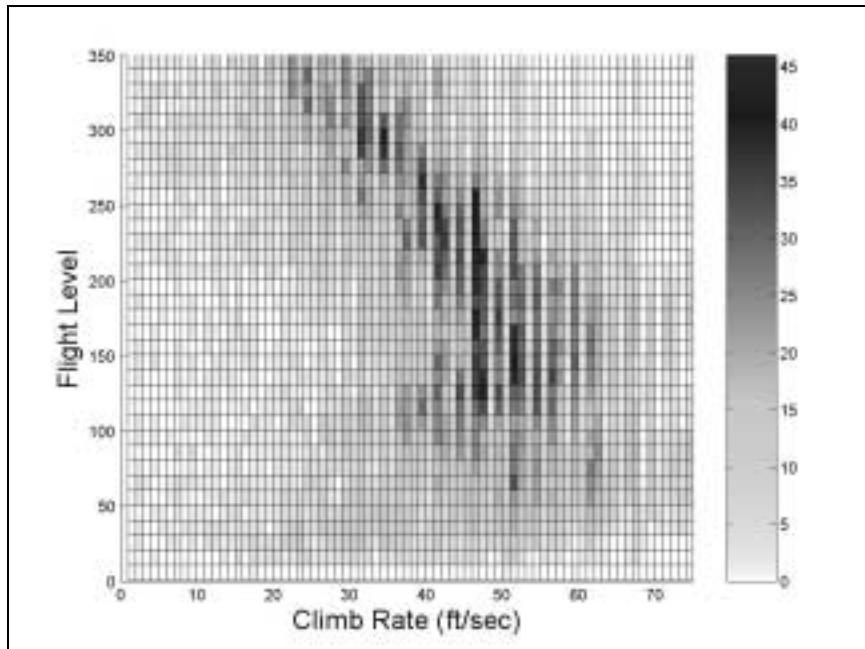


Figure 37: B737 Climb Rate Distribution

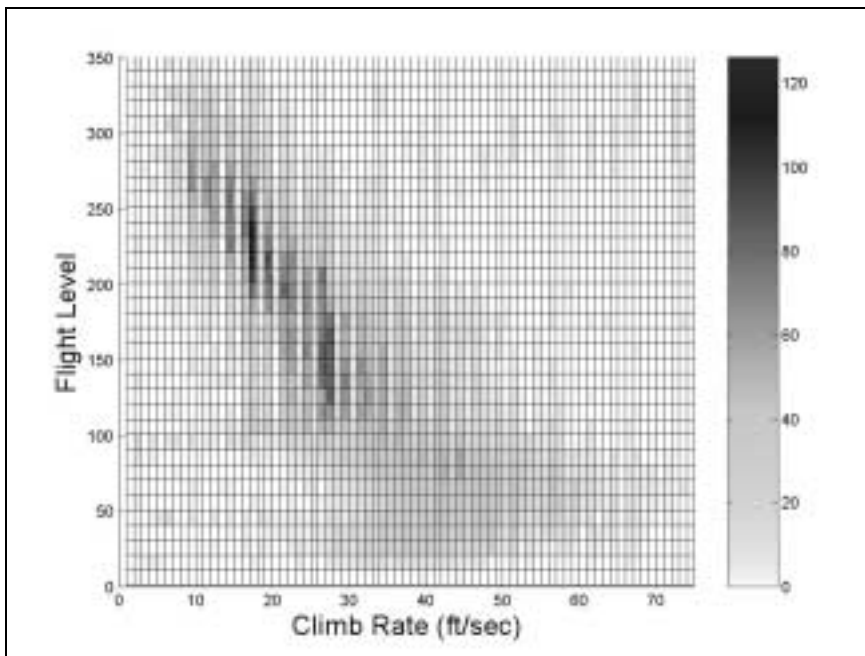


Figure 38: CRJ2 Climb Rate Distribution

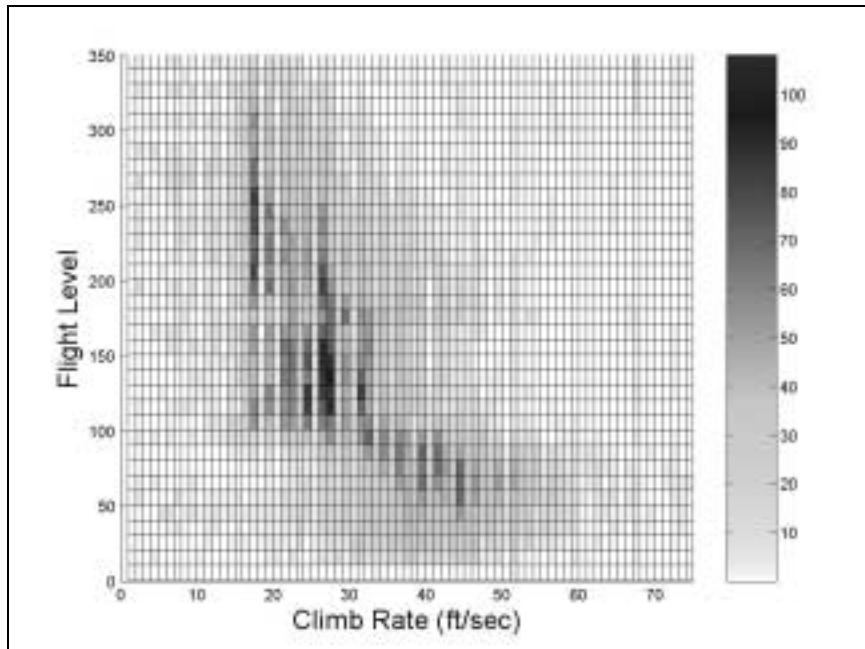


Figure 39: E145 Climb Rate Distribution

7 Possible Consequences of Regional Jet Growth

It was shown in section 3 that regional jet operations have a high density in the same areas of the country as other aircraft categories, in particular narrow body jets and turboprops. The interaction of aircraft in these dense areas may result in operational problems since the different aircraft types do not exhibit the same performance. Regional jets were observed to exhibit lower climb rates than traditional jets, which may impact air traffic control handling and sector design. It was also observed that as regional jets replace turboprops, they compete for runways and take off trajectories with narrow body jets. The combination of the different performance and the competition for resources between regional and other jets, may pose problems for air traffic control. If problems are observed they will be congestion related, which will result in delays and increased workload for controllers. The problems can be broken down into three categories based on where in the system they may occur. The three categories are airport congestion, terminal area congestion, and en route congestion.

7.1 Airport Area

In the airport, the main consequences resulting from increased regional jet operations will be congestion related and will be a result of aircraft competing for resources. Regional jets typically need to use the same runways as traditional jets, whereas turboprops often use shorter ones. As regional jets replace turboprops and as the number of regional jets increases, they will be competing for runway space, and may exacerbate congestion problems, as the number of operations per person will increase. To examine the likelihood of this problem, surface area diagrams for a few major airports

were examined. Figure 40 shows the surface diagram for ATL. It is clear from the figure that all the runways at this airport are long and therefore turboprop replacement by regional jets will not cause runway related delays. A slightly different situation exists at both Dallas Forth Worth (DFW) and Newark (EWR), as can be seen in Figures 42 and 43 respectively. In this case both airports have long or primary and short or secondary runways. While the secondary runways are still sufficient for use by regional jets, Newark airport released a study which showed that regional jet pilots are resistant to using them, citing safety concerns. As a result of this resistance, Newark recorded that the short runway usage decreased 65% between 1995 and 1999, while the number of regional jet operations increased 300%. Due to these changes Newark has experienced a significant increase in the usage of their primary arrival and departure runways and increased delays. [24]

The congestion problems resulting from competition for primary runways can be alleviated by convincing regional jet pilots to use secondary runways whenever possible. This can be accomplished through either incentives and/or disincentives, such as higher landing fees for primary runways and lower fees for secondary runways. Providing pilot training to make the pilots feel that using the shorter runways is safe may also help the problem. However, if the regional jet pilots cannot be successfully convinced to use secondary runways there is the hope that new communication, navigation, and surveillance (CNS) technology will help decrease the required take off separation between aircraft and result in a higher utilization of the primary runways.

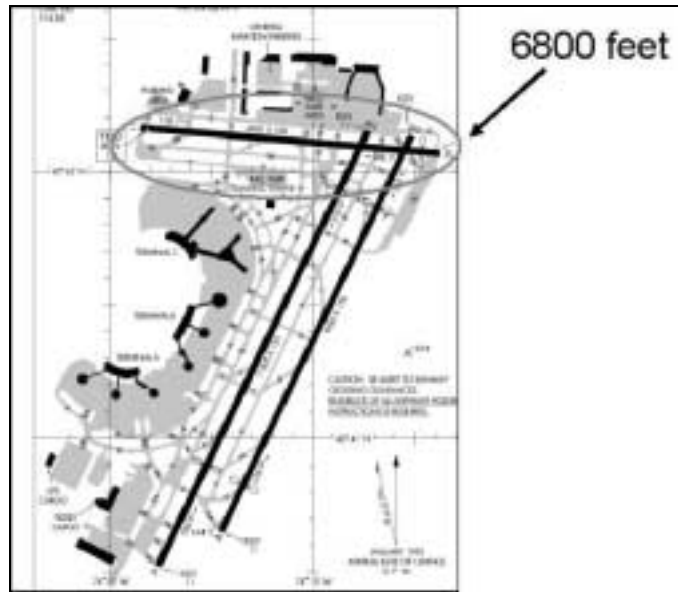


Figure 42: EWR Surface Diagram

7.2 Terminal Area

Airports may also see increased congestion on departure and arrival tracks. Figure 43 shows the flight tracks for departures from DFW on January 9th 2003 between 0000 and 0500 GMT. The black lines indicate turboprop trajectories, and the blue and green lines represent regional and traditional jet trajectories. It can be seen that regional and traditional jets align on the same tracks, while turboprops fly on separate routes. As regional jets replace turboprops and as the number of regional jets grows, an increase in congestion on the jet arrival and departure routes is expected.

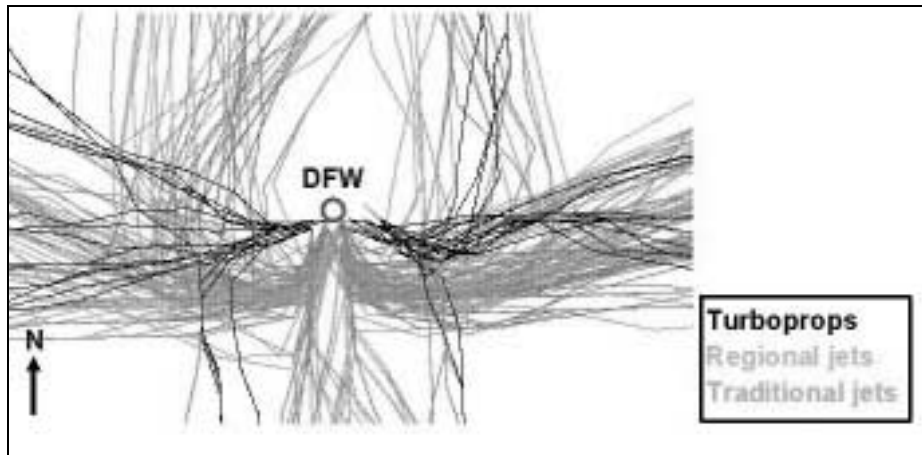


Figure 43: DFW Take off Tracks for Departures between 0000 and 0500 GMT

In addition to congestion issues due to an increase in operations, congestion and delay issues may also appear due to climb performance differences between regional and traditional jets. The slower climb rate of regional jets may increase the range of aircraft performance that controllers must manage in order to adhere to proper separation standards. Slower climb rates can change how regional jets interact with the sector structure. Many of the irregular sector shapes found in the current air traffic management system are a direct consequence of modifications targeted at reducing the number of sector boundary crossings. Boundary crossings are avoided due to the increased radio communications and coordination workload associated with each transition. Figure 44 shows climb rates overlaid with a hypothetical sector structure. It can be seen from the figure how the slower climb performance of regional jets could increase the number of sector boundary crossings. This implies that some departure sectors may need to be redesigned in order to accommodate this new range of aircraft performance. The dotted line in the figure shows the proposed new boundary for the lower sector.

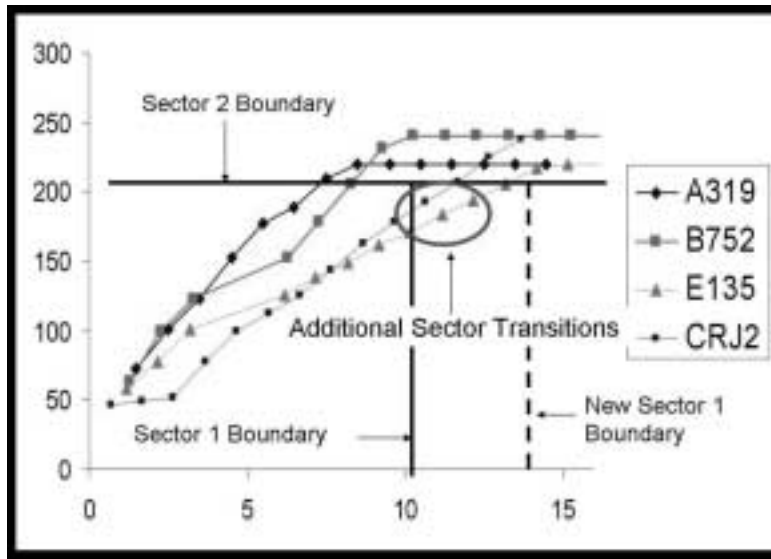


Figure 44: Missed Sector Crossing due to Slow Climb Rate

It was shown in Figure 43 that traditional jets and turboprops are separated into different tracks soon after departure, minimizing the interaction between the two aircraft types. This idea could be used to separate regional jet flights from other jet flights so that the slower climb of regional jets would not hold back the other aircraft, and so the jet take off tracks would not become too congested. However, many regional jet flights share cruise tracks with traditional jets and if the two aircraft types were separated they would have to be merged back together once at altitude. The separation and the subsequent merge would both increase the workload of the controllers. A better solution may be to simply level out the regional jets at a lower altitude so that the traditional jets can climb at an unobstructed rate. The histograms of speed and cruise altitudes, shown in Figures 32 through 35, suggest that controllers are already using this tactic, which would partially explain why regional jets cruise at a lower altitude than narrow body traditional jets even though they are capable of the same speeds during cruise.

To address the problem of missed sector transitions a number of possible solutions can be adopted. First, the trajectory between the origin and the boundary crossing point can be elongated to give the aircraft more time to climb. Second, the sector boundary can be moved either down or further. Finally, since when a missed crossing occurs the time that the aircraft spends in the addition sector is probably very brief, controller procedures that would allow the aircraft to cut through a corner of a sector without making a full transition can be used.

7.3 En Route Congestion

In addition to congestion at the airport and terminal areas, there is also a concern for en route congestion where regional jets share routes with other jets. However, as shown in the previous section regional jets are capable of cruising at very similar speeds as narrow body jets, which means that their performance would not cause additional congestion. This does not mean that en route congestion is not a problem for air traffic control. As the number of planes in the system increases, and as the number of regional jets grows congestion issues will be more and more pressing. If the slight difference in the performance of regional and other jets becomes more significant, further separation of the two aircraft types by altitude will help to alleviate the problem.

7.4 Summary of ATC Concerns

As shown above, the difference in the performance and the competition for resources between regional jets and other aircraft may create congestion problem for ATC. However, these problems will not affect all aspects of operations. In particular, it was shown that competition for resources may add to congestion problems at airports with

both primary and secondary runways and in jet arrival and departure tracks. It was also shown that regional jets exhibit a slower climb rate than traditional jets and as a result may slow down departing traffic and possibly result in missed sector transitions. It was also determined that the performance of regional jets during cruise will have little influence on congestion.

8 Conclusions

8.1 Summary of Findings

Airlines are increasingly using regional jets to better match aircraft size to high value, but limited demand markets. The increase in regional jet usage represents a significant change from traditional air traffic patterns. To investigate the possible impacts of this change on the air traffic management and control systems, this study analyzed the emerging flight patterns and performance of regional jets compared to traditional jets and turboprops. This study used ASDI data, which consists of actual flight track data, to analyze flights between January 1998 and January 2003. In addition, a study of regional jet economics, using Form 41 data, was conducted in order to better understand the observed patterns.

It was found that in 1998 US regional jet patterns and utilization closely resembled those of the turboprops. Both aircraft were used for hub feeder operations. They flew relatively short distances, under 500 nautical miles, and exhibited similar cruise altitudes and speeds. These patterns began to change as the number of regional jets increased. By January 2003, the regional jets were no longer used solely for hub feeder operations, but were flying longer routes at higher altitudes and faster speeds than turboprops. As a result, regional jets have come to fill a gap in the market by flying on longer routes than the turboprops, but shorter than the narrow body jets.

An economic analysis was conducted in order to better understand the observed regional jet patterns. It was found that regional jets have lower operating costs per trip and higher operating costs per ASM than traditional jets. As a result, regional jets are

currently a lower cost alternative for traditional airlines because they cover the cost of regional jet flights on a per departure basis. However, if this structure were to change regional jets would become a less appealing alternative. To better understand the consequences of a change in the operation patterns, changes in the cost of regional and traditional jets were analyzed when trip length and pilot costs per block hour were normalized. It was found that regional jet costs per trip are very similar to traditional jet costs per trip when the trip length between the two aircraft categories is normalized, but that the normalization of pilot cost per block does not have a significant effect on the relative costs of the two aircraft types.

In 2003, the US regional jet operations showed a high density of flights in the north-eastern part of the country. This part of the US also has the largest concentration of traditional jet operations; this interaction may result in congestion problems since the two types of aircraft exhibit different performance. In particular, regional jets were observed to exhibit lower climb rates than traditional jets, which may impact air traffic control handling and sector design. It was also observed that as regional jets replace turboprops, they compete for runways and take off trajectories with narrow body jets. The combination of the different performance and the competition for resources between regional and other jets may result in increased delays and congestions as well as increased controller workload.

The future growth of regional jets is uncertain. However, currently both US Airways and Jet Blue have placed orders for new Embraer aircraft indicating that the growth of regional jets will continue for the time being. In addition, both Embraer and Bombardier are currently designing and manufacturing larger regional jets. These aircraft will be

designed to accommodate more passengers on further trips and as a result will further change the composition and performance capabilities of the national fleet.

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Appendix A. ASDI Filtering Algorithm

The following is an excerpt from the Aircraft Situation Display To Industry Functional Description and Interface Document. It outlines the specific methods for filtering ETMS data before it can be passed on to vendors.

1. Check to see if the message is an allowed type. If not, e.g., the message is a BZ message, then the message is discarded; it does not go out in the ASDI feed. If it is valid, it is passed to the next step.
2. Look at the code in the message that shows the facility that generated the message. If the code is not in the configuration file that specifies legal facilities, then discard this message; it does not go out in the ASDI feed. If the code is in this file, then pass it to the next step. (Note: There are two feeds--one that contains London data and one that does not. This configuration file controls for each feed whether London data is included.)
3. Look at the aircraft call sign. If it is in the File of Forbidden Call Signs, then discard it; it does not go out in the ASDI feed. If it is not in this file, then pass it to the next step. (The File of Forbidden Call Signs, which is maintained by the Air Traffic Control System Command Center, contains call signs of non-military flights that are considered to be sensitive.)
4. Check to see if the call sign starts with 'N' followed by a digit followed by a digit or letter. That is, check to see if the first three characters of the call sign have the format 'Ndd' or 'Ndl', where 'd' stands for digit and 'l' for letter. If so, this is considered to be a GA flight; it goes out in the ASDI feed. If not, then this flight is passed to the next step.
5. Check to see if the call sign is exactly 5 letters, the first two of which are 'CF' or 'CG'. If so, this is considered to be a Canadian GA flight; it goes out in the ASDI feed. If not, then this flight is passed to the next step.
6. Check to see if the call sign starts with 'LN' followed by a digit followed by a digit or letter. That is, check to see if the first four characters of the call sign have the format 'LNdd' or 'LNdl', where 'd' stands for digit and 'l' for letter. If so, this is considered to be a lifeguard flight; it goes out in the ASDI feed. If not, then this flight is passed to the next step.
7. Check to see if the call sign starts with 'TN' followed by a digit followed by a digit or letter. That is, check to see if the first four characters of the call sign have the format 'TNdd' or 'TNdl', where 'd' stands for digit and 'l' for letter. If so, this is considered to

be an air taxi flight; it goes out in the ASDI feed. If not, then this flight is passed to the next step.

8. Check to see if the call sign is three letters followed by a digit. If not, the flight is considered to be military and is discarded; it does not go out in the ASDI feed. If so, this is considered to be a commercial flight; pass it to the next step.
9. Check the first three letters of the call sign to see if they represent an airline for which messages are to be sent in the feed. (The Radiotelephony file, which is maintained by the Air Traffic Control System Command Center, specifies the airlines whose messages are to be included in the feed.) If so, this message is sent out in the ASDI feed. If not, discard this flight; it does not go out in the ASDI feed.

Appendix B. ETMS Data Dates Used in Study

The following is a list of the days for which data was obtained in order to conduct this research.

Date(Y/M/D)	Day
1998/01/22	Thursday
1999/01/21	Thursday
2000/01/13	Thursday
2001/01/11	Thursday
2002/01/10	Thursday
2003/01/09	Thursday

Appendix C. Classification of Aircraft into Categories

The following is a list of aircraft included in each of the four aircraft categories. The % sign acts as a wild card, so that as long as what appears before the % sign is matched that aircraft type is included in the category.

Narrow Body Traditional Jets:

A318
A319
A32%
B70%
B71%
B72%
B73%
B75%
DC8%
DC9%
MD8%
MD9%
F70%
F100
B4%

Wide Body Traditional Jets:

A30%
A310
A312
A313
A31C
A33%
A34%
B74%
B76%
B77%
DC1%
MD1%

Regional Jets

RJ%
BA46
CRJ%
E1%

Turboprops

B190
SF34
DH8A
DH8B
BE20
C208
SW4
JS4
JS41
DH8C
AT72
MU2

Appendix D. Distance Histograms

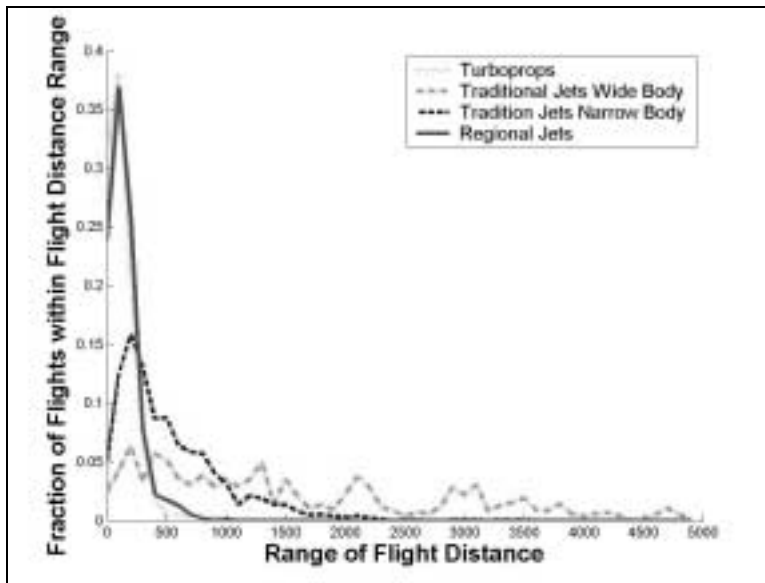


Figure 45: January 1998 Distance Histogram

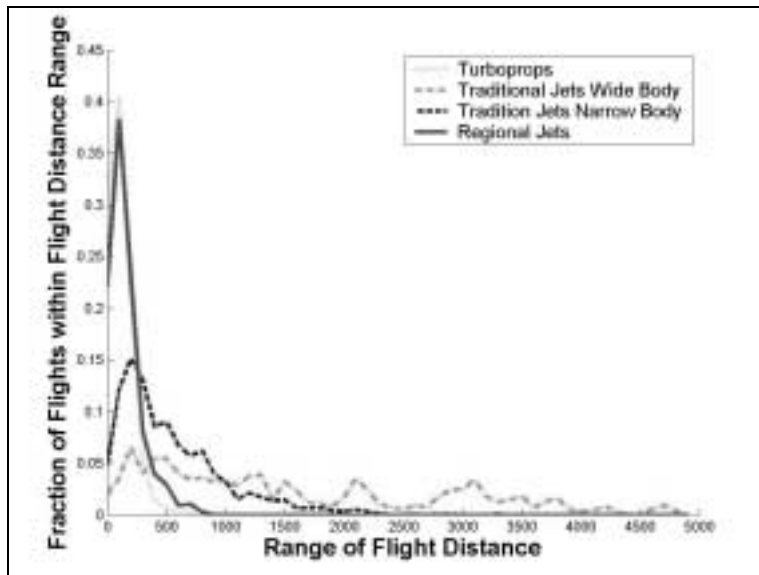


Figure 46: January 1999 Distance Histogram

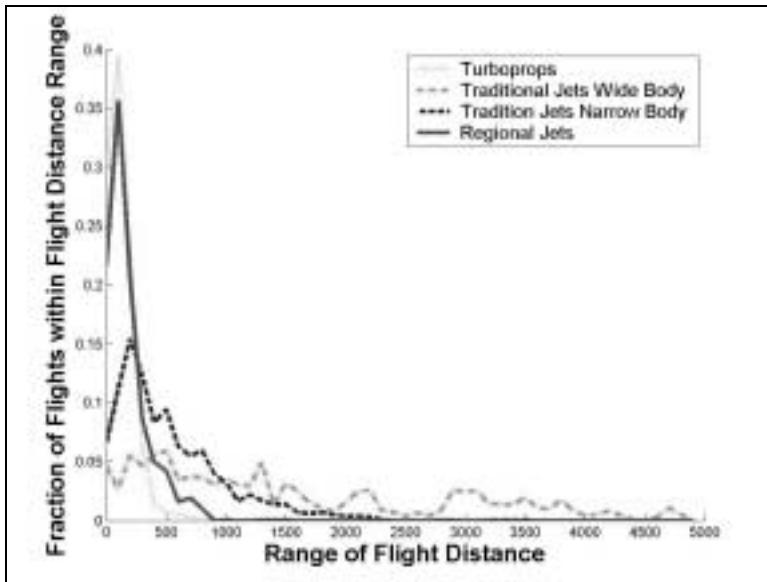


Figure 47: January 2000 Distance Histogram

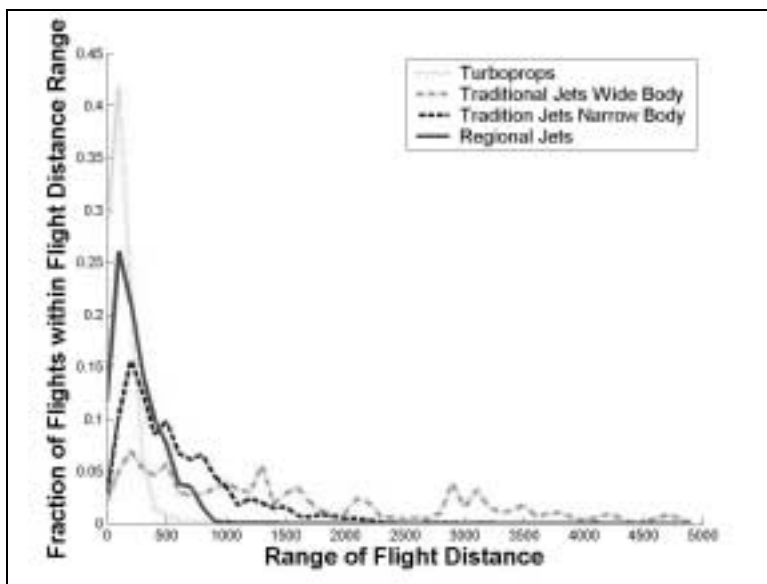


Figure 48: January 2001 Distance Histogram

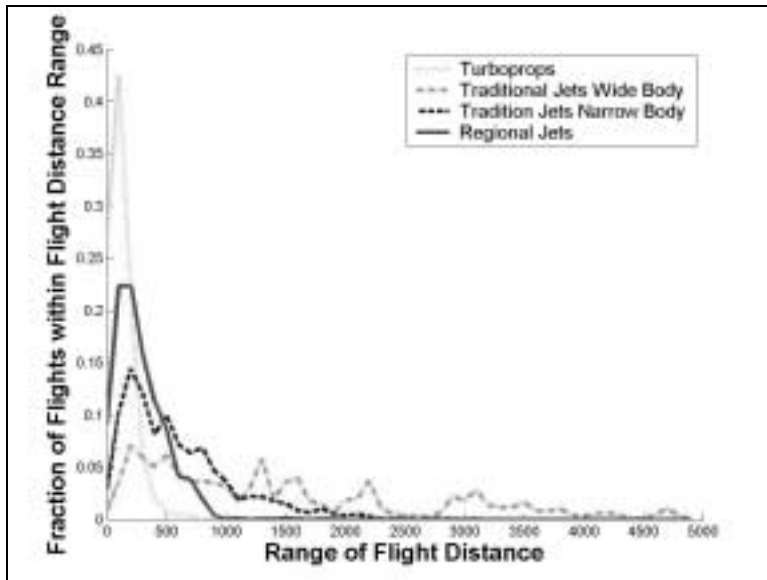


Figure 49: January 2002 Distance Histogram

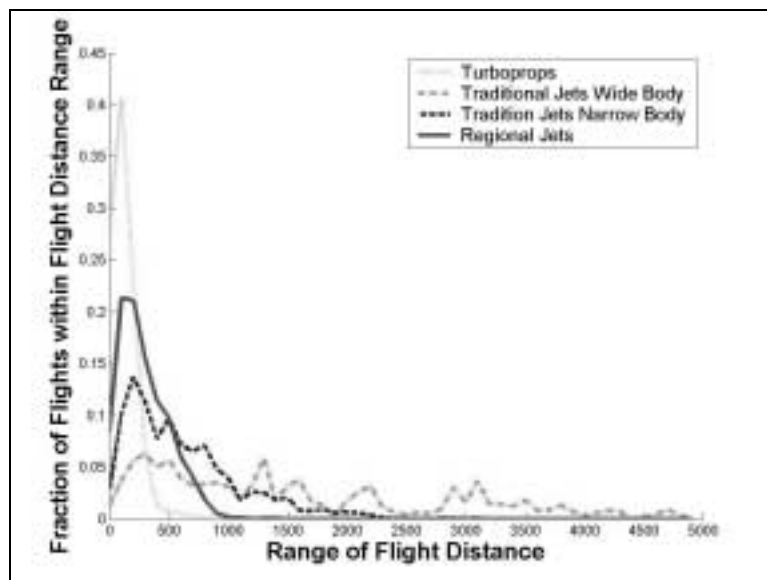


Figure 50: January 2003 Distance Histogram

Appendix E. Catchment Basin Plots

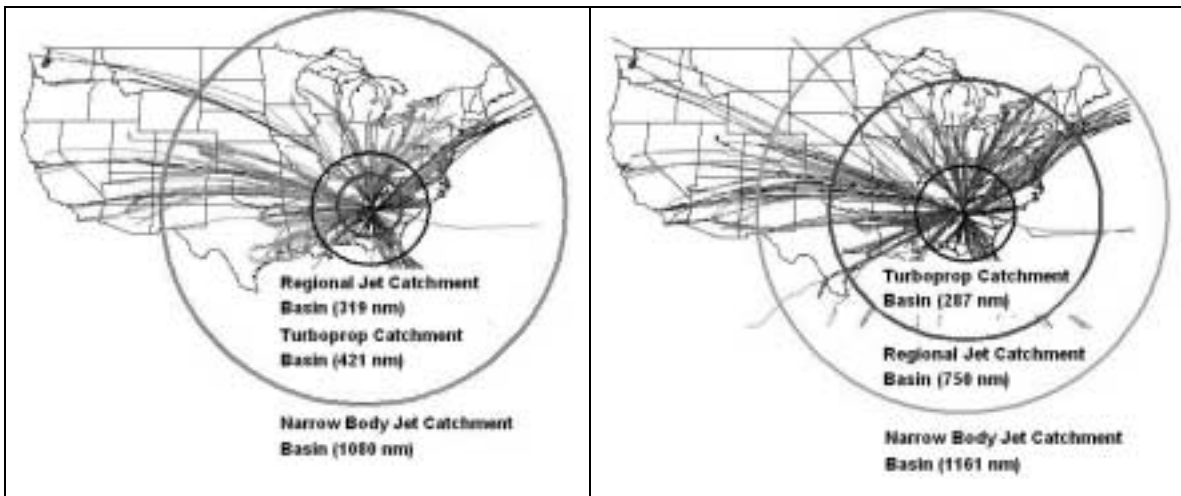


Figure 51: ATL Catchment Basin Changes between 1998 and 2003

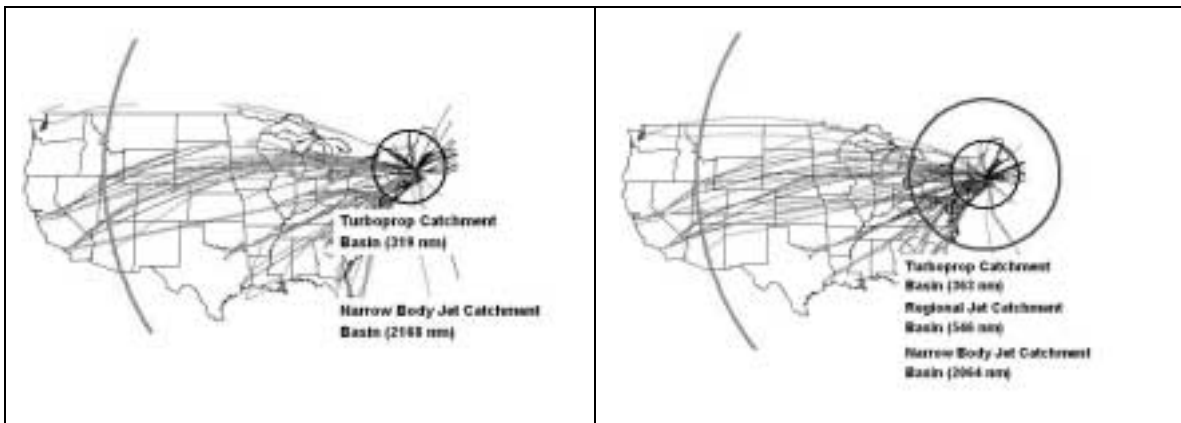


Figure 52: BOS Catchment Basin Changes between 1998 and 2003

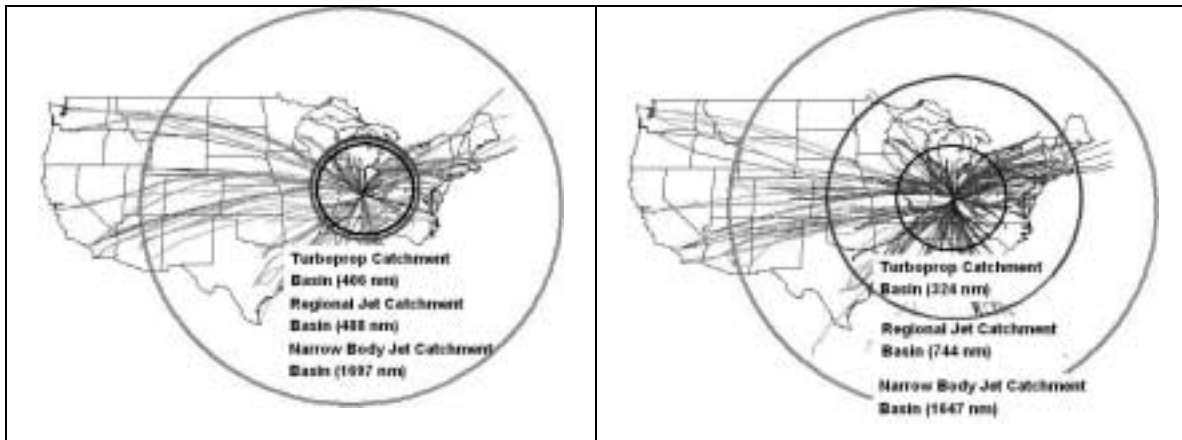


Figure 53: CVG Catchment Basin Changes between 1998 and 2003

Appendix F. Regional Jet Economic Model

The economic model used to study and compare the cost structure of regional and traditional jet aircraft used in chapter 4 calculates the total aircraft expenses according to the following formula:

$$New_Total_Cost = [(OFOE - OPC + (\frac{NPC}{OBH}) * NBH) * \frac{NBH}{OBH}] + MC + OC$$

where:

OFOE	Old Flight Operating Costs
OPC	Old Pilot Costs
NPC	New Pilot Costs
OBH	Old Block Hours
NBH	New Block Hours
MC	Maintenance Costs
OC	Operating Costs

As can be seen the flight operating costs are scaled with block hours, the maintenance costs were scaled according to the number of flights (which remained constant), and the ownership costs were calculated based on estimated price of aircraft as well as an assumed loan time and interest.

When calculating the cost per ASM, a new value for ASMs needed to be calculated if trip length changed. This calculation was done according to the following formula:

$$New_ASM = \#Seats * Trip_Length * \#Trips$$

Appendix G. List of Hub and Major Airports

The following is a list of the codes and name of airports that were counted as hubs for the point-point service study.

ATL The William B Hartsfield Atlanta International Airport
BOS General Edward Lawrence Logan International Airport
ORD Chicago O'Hare International Airport
LGA La Guardia Airport
JFK John F Kennedy International Airport
EWR Newark Liberty International Airport
PHL Philadelphia International Airport
BWI Baltimore-Washington International Airport
DCA Ronald Reagan Washington National Airport
PIT Pittsburgh International Airport
IAD Washington Dulles International Airport
RDU Raleigh-Durham International Airport
CLT Charlotte Airport
MIA Miami International Airport
CLE Cleveland Airport
DTW Detroit Metro Airport
CVG Cincinnati/Northern Kentucky International Airport
MEM Memphis International Airport
STL St Louis International Airport
MSP Minneapolis-St. Paul International Airport
DFW Dallas/Fort Worth International Airport
IAH George Bush Intercontinental Airport/Houston
DEN Denver International Airport
SLC Salt Lake City International Airport
PHX Phoenix Sky Harbor International Airport
LAX Los Angeles International Airport
SFO San Francisco International Airport
SEA Seattle-Tacoma International Airport

Appendix H. Summary of Scope Clause Restrictions

The Regional Air Service Initiative compiled the following scope clause restriction summary. [18]

Carrier	Maximum Seats		Maximum Weight		Allowed Number	Other Limitations
	No limit	Limit	No limit	Limit		
Alaska Airlines	No limit	No limit	No limit	No limit	None	None
America West Airlines I/	50	70	45 +3 per each mainline aircraft over baseline	15 +2 per each mainline aircraft over baseline	None	None
American Airlines	90	50	25	Unlimited	CRJ700 aircraft to be flown by mainline subject to achieving American Eagle economics	(1) Total regional aircraft <110% of mainline narrowbody aircraft; (2) <1% of flying between key airports (DFW, ORD, MIA, JFK, SFO, LAX, LGA, STL and SBU); (3) 85% of all RJ flying must be from 40 key airports. Regional must be owned by ATA
ATA	70	85,000 lbs.	53 plus 3 ATA aircraft above 58 to a maximum of 120			
Continental Airlines	59	No limit	Unlimited			
Delta Air Lines	50	65,000 lbs.	Unlimited			(1) Maximum 15% of stage lengths 900+ miles; (2) Maximum of 10% of nonhub flying; (3) Maximum of 6% inter-hub flying (except TPA, FLL, ORL); (4) Regional block hours <16% and 37% of Delta block hours in 2003 and 2004 respectively
Northwest Airlines	44	No limit	Unlimited			No Northwest regional may operate aircraft 60+ seats or 70,000-lbs.
Southwest Airlines	55	70,000 lbs.	Depends on number of Northwest narrowbody fleet. If 332, then base number of RJs = 30; Add one RJ for each Northwest narrowbody 347+; If <360 ± 12,000, then reduce base number of RJs by the difference; May add one RJ for each Aereo RJ retired			(1) All flights must be flown to/from a Northwest hub or international gateway; (2) No flights between hubs or gateway and hub unless gateway is BOS, PHL, LAX, FPA and such flying is <5% of RJ block hours; (3) RJs at Mesa, Phoenix, and other regionals owned by Northwest must use Northwest flight numbers
United Airlines	No limit	No limit	No limit	No limit	None	None
USAirways	70	80,000 lbs.	Unlimited			(1) Regional block hours < mainline block hours; (2) 90% of flying to/from key cities; (3) TBD portion of 50+ seat RJs to be flown by furloughed United Pilots
			(1) Small RJ: 44 seats (includes CRJ240/410 with 40 seats)	150		(1) 70 medium RJs may fly for any regional; (2) All other small RJs must fly for "participating" regionals, with half the jobs reserved for furloughed USAirways Pilots under Jets for Jobs; (3) Mesa may fly 20 medium RJs plus 30 CRJ700s with ALPA labor and Jets for Jobs; (4) 25 CRJ700s may fly for another affiliate under Jets for Jobs; (5) 25 CRJ700s fly for a USAirways subsidiary carrier under Jets for Jobs; (6) Chattanooga and Midway may fly medium RJs briefly outside of Jets for Jobs so long as they ultimately conform; (7) All other large RJs must fly for USAirways division MidAtlantic; (8) 60% of all medium RJs 140+ seats fly for MidAtlantic
			(2) Medium RJ: 50 seats	65,000 lbs.		
			(3) Large RJ: 70 seats (includes EMB-170 and EMB-175 with maximum of 76 seats)	75,000 lbs.	Medium RJs and large RJs <315. Add two large or medium RJs per USAirways mainline aircraft 315+	

Appendix I. Cruise Altitude Histograms

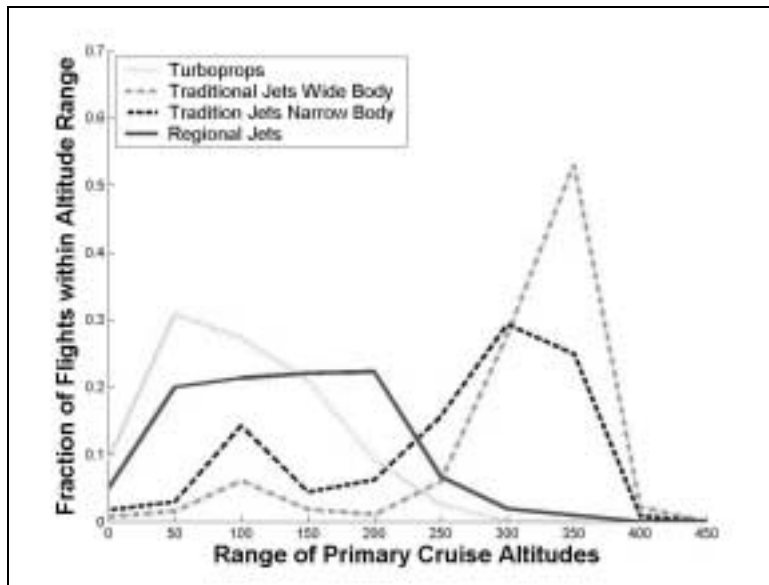


Figure 54: January 1998 Primary Cruise Altitude Histogram

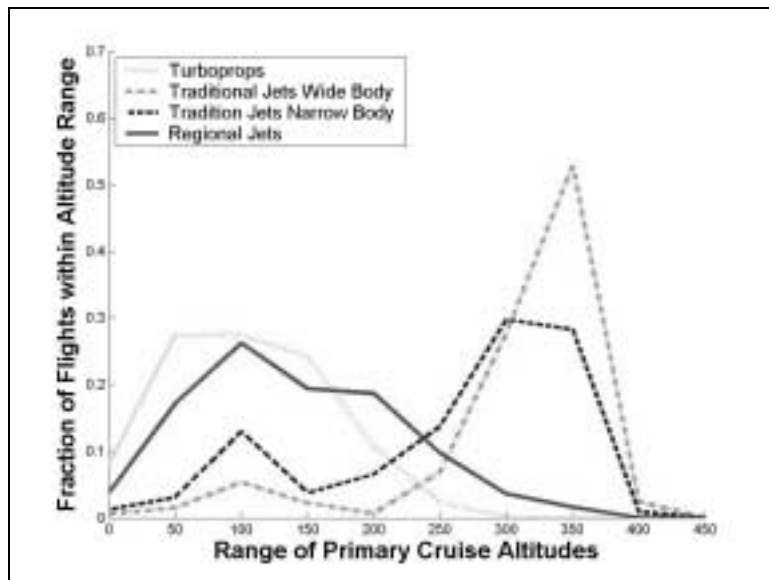


Figure 55: January 1999 Primary Cruise Altitude Histogram

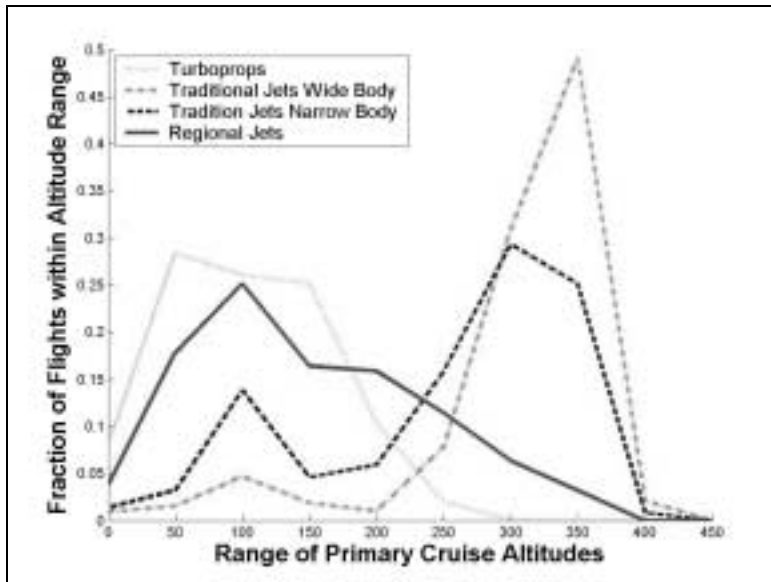


Figure 56: January 2000 Primary Cruise Altitude Histogram

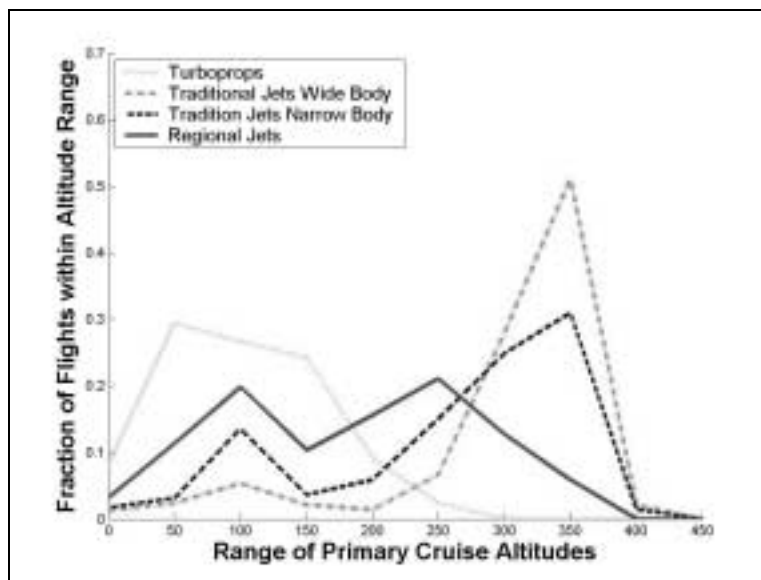


Figure 57: January 2001 Primary Cruise Altitude Histogram

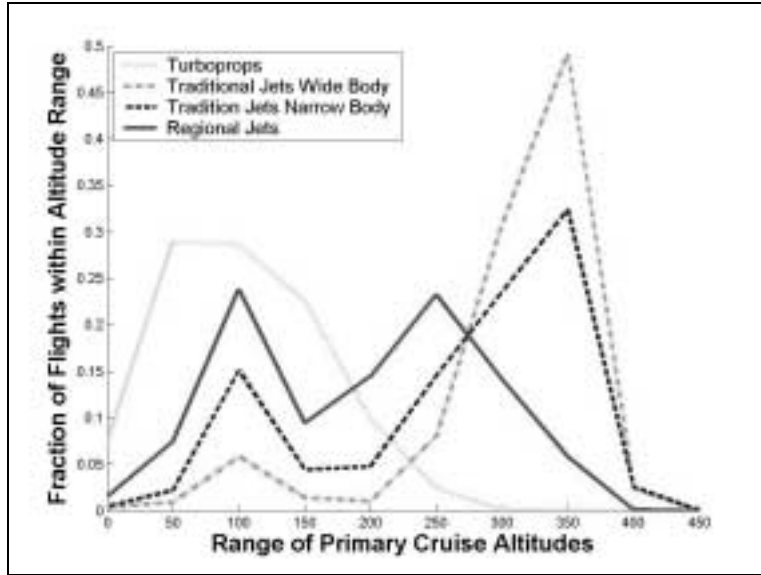


Figure 58: January 2002 Primary Cruise Altitude Histogram

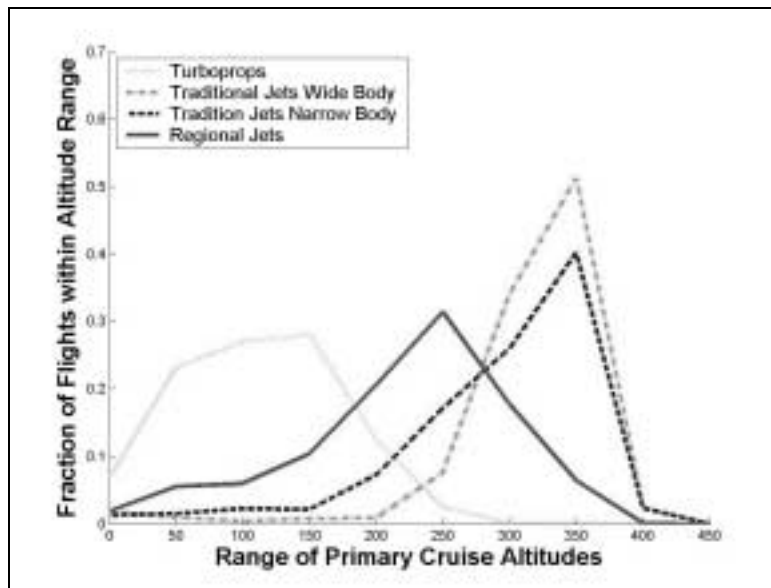


Figure 59: January 2003 Primary Cruise Altitude Histogram

Appendix J. Cruise Speed Histograms

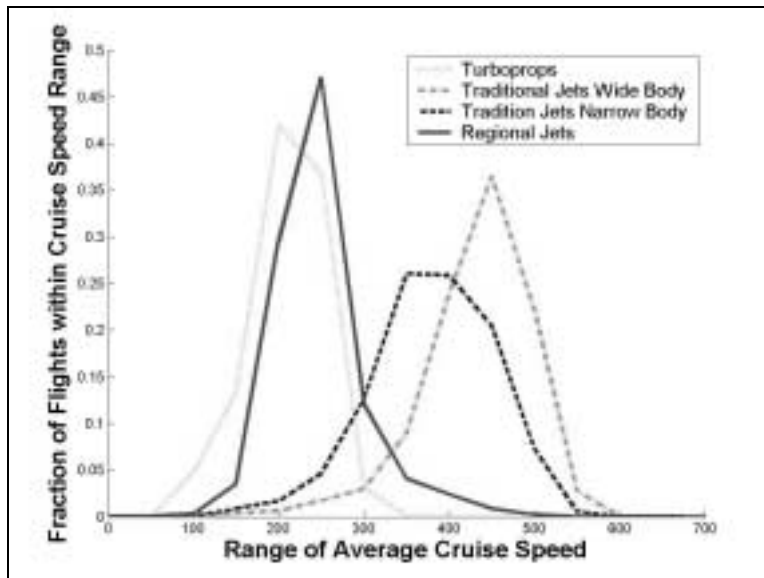


Figure 60: January 1998 Average Cruise Speed Histogram

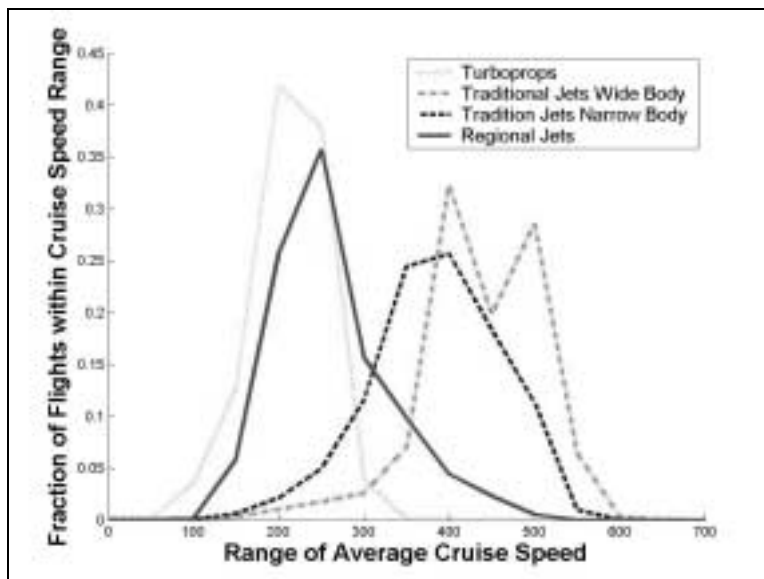


Figure 61: January 1999 Average Cruise Speed Histogram

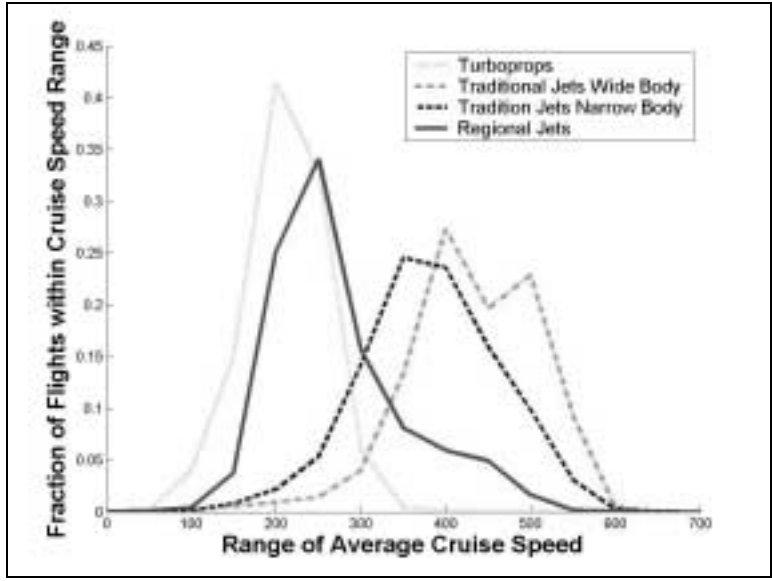


Figure 62: January 2000 Average Cruise Speed Histogram

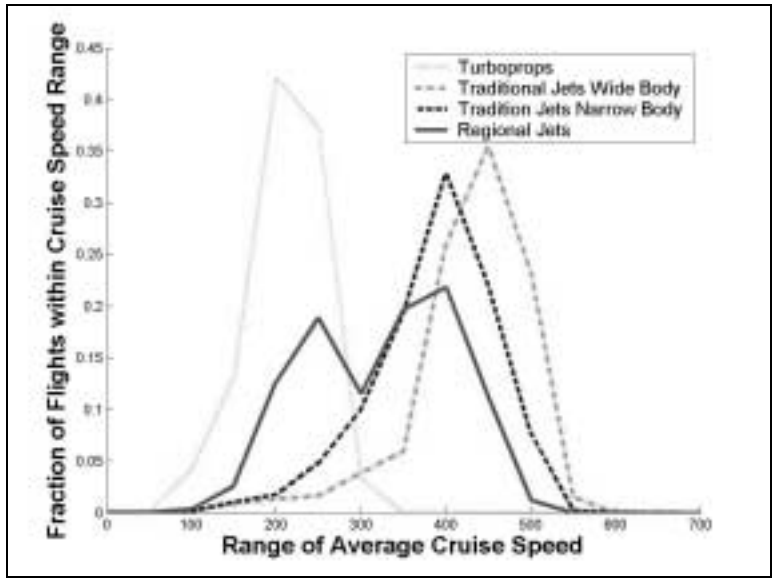


Figure 63: January 2001 Average Cruise Speed Histogram

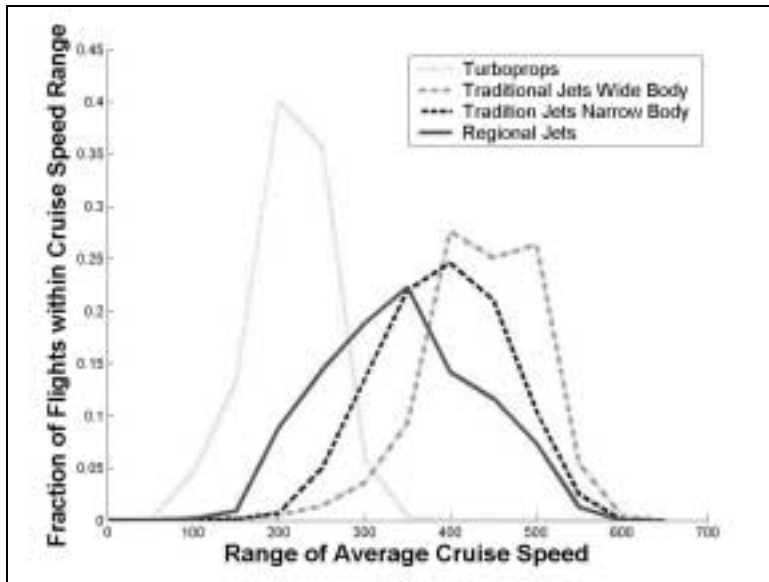


Figure 64: January 2002 Average Cruise Speed Histogram

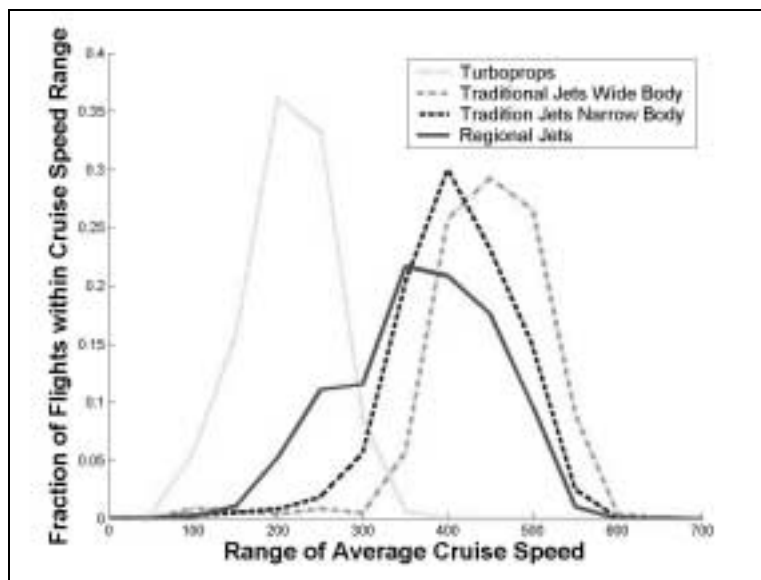


Figure 65: January 2003 Average Cruise Speed Histogram

Appendix K. Climb Rate Distributions

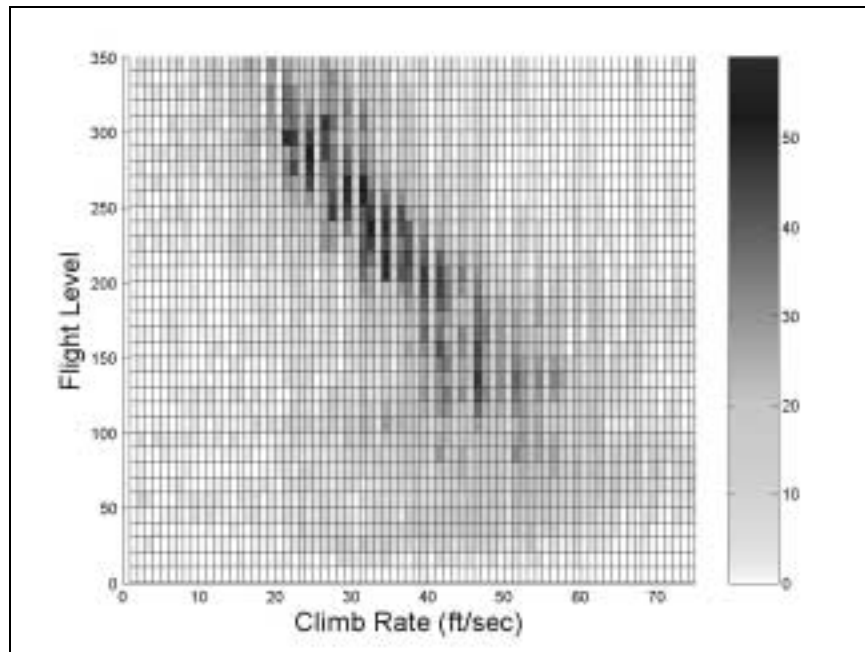


Figure 66: A319 Climb Rate Distribution January 2003

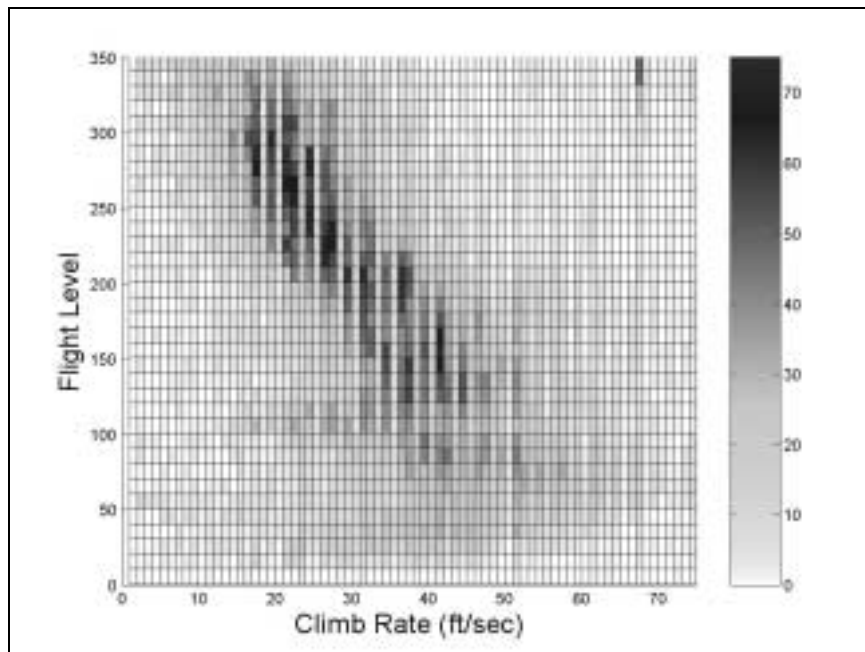


Figure 67: A320 Climb Rate Distribution January 2003

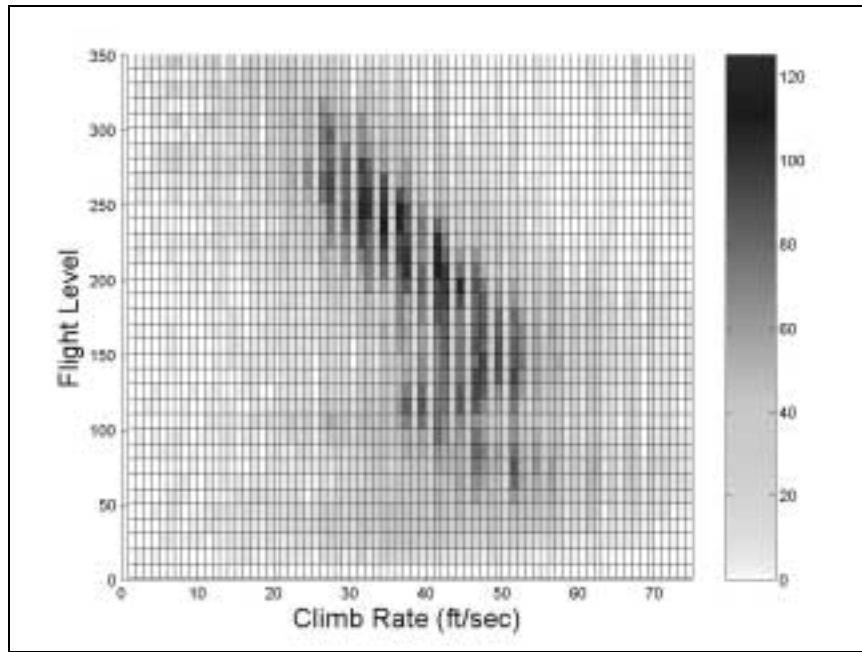


Figure 68: B733 Climb Rate Distribution January 2003

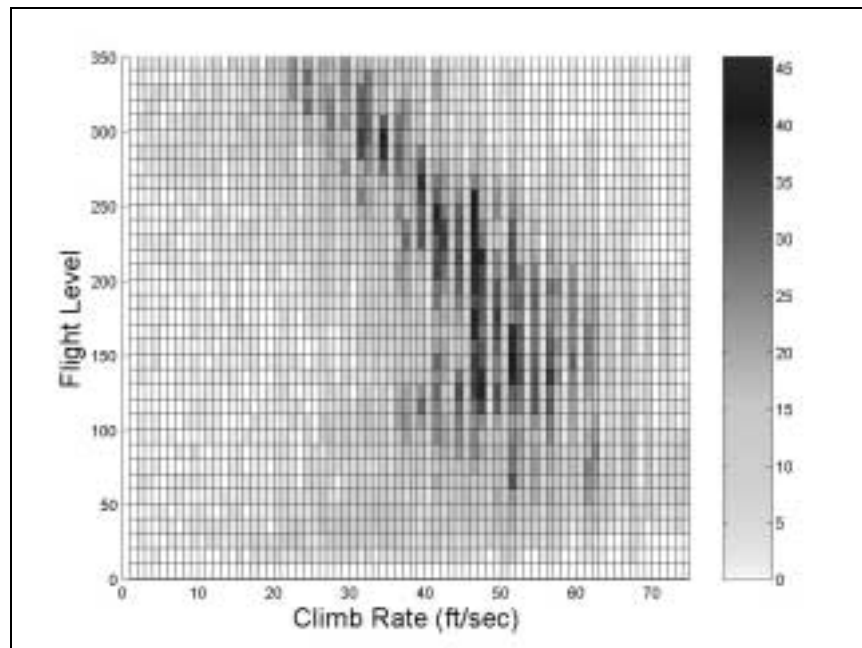


Figure 69: B737 Climb Rate Distribution January 2003

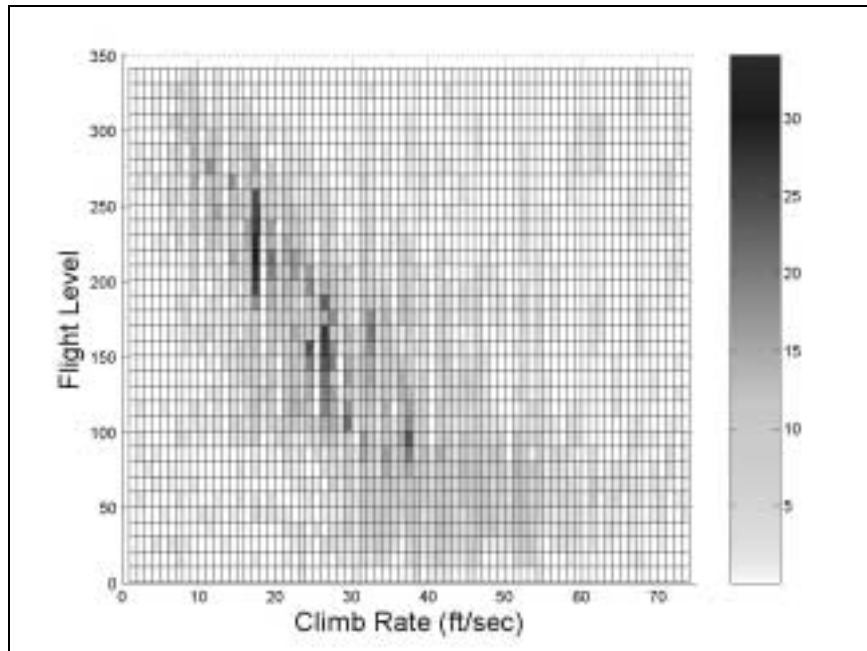


Figure 70: CRJ1 Climb Rate Distribution January 2003

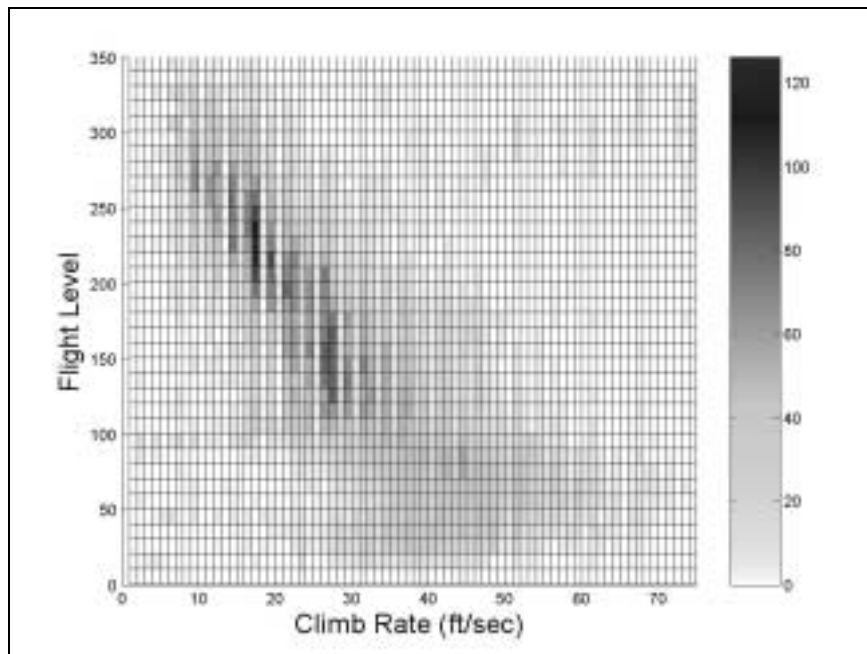


Figure 71: CRJ2 Climb Rate Distribution January 2003

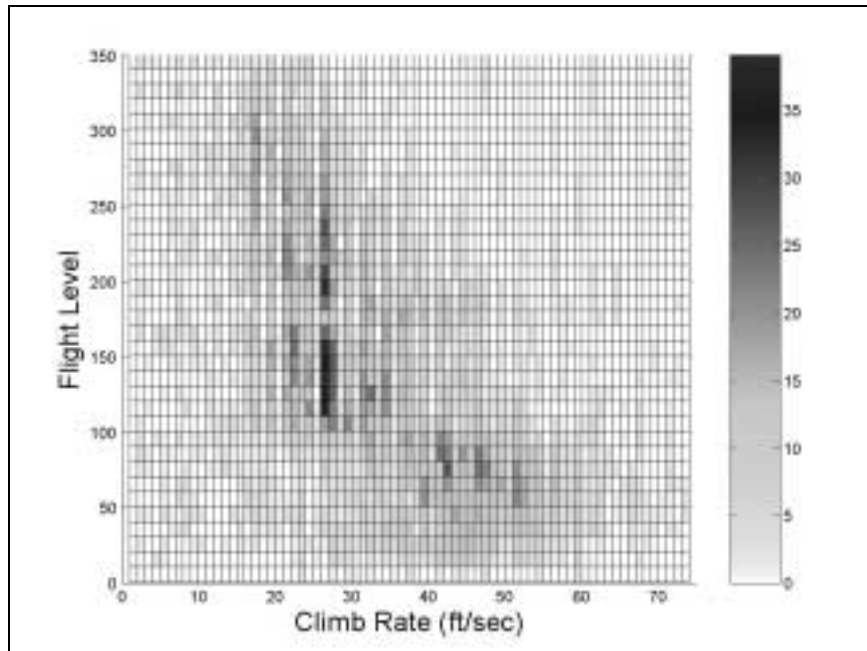


Figure 72: E135 Climb Rate Distribution January 2003

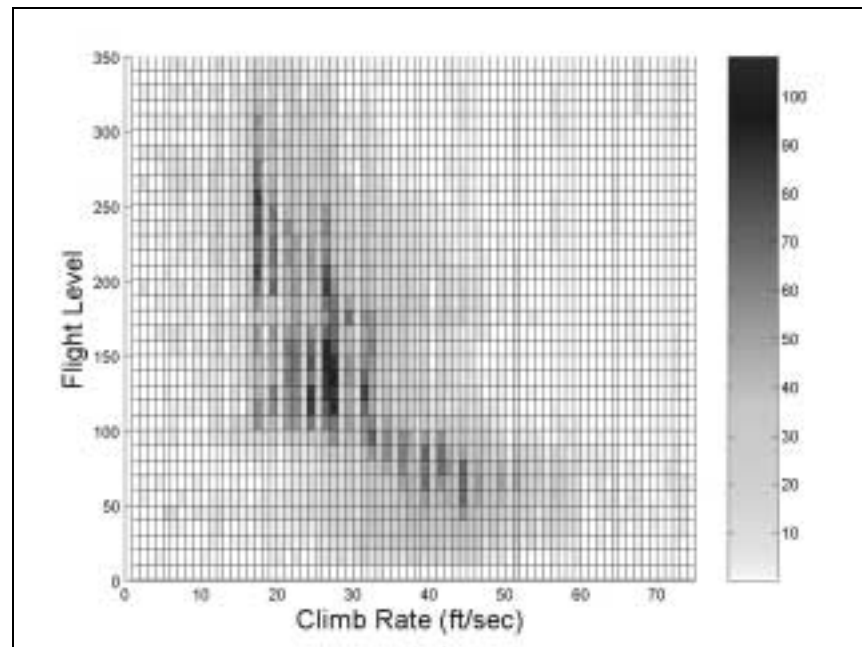


Figure 73: E145 Climb Rate Distribution January 2003