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Relationships Between Aircraft Fleet Composition and Environmental Impacts

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Abstract

Aviation is a growing industry with its own set of environmental impacts such as high altitude greenhouse gas emissions, use of nonrenewable fuels, and stresses to communities surrounding airports. The industry is under increasing pressure to address its impacts. One of the things that affects impacts is fleet composition. The current research mainly covers operational impacts of greenhouse gas and noise emissions of individual aircraft. In order to establish a relationship between the composition of aircraft fleets and environmental impacts, this thesis used four analyses. These analyses examined fuel consumption, exhaust emissions, noise emissions, and infrastructure congestion. A couple of generalized types of aircraft that were used for comparison were narrow versus wide body aircraft and newer versus older aircraft. It was found that older aircraft have larger environmental impacts, and the wide body aircraft do not always benefit from economies of scale in terms of environmental impacts. It was also found that airport size is more closely related to congestion than the type of route networks run from the given airport.

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Introduction

The aviation industry has grown massively since the middle of the twentieth century. Demand for air transportation, size of aircraft, and number of aircraft movements have all increased. Furthermore, the International Civil Aviation Organization predicts a passenger traffic growth rate of 4.6 percent each year until 2025 (ICAO, 2007).

A 50-fold growth of passengers in roughly half a century has increased environmental impacts from the industry despite efficiency gains. Aviation is currently a small contributor to climate change, contributing less than ten percent of human induced radiative forcing. Radiative forcing is the change in energy balance in the earth's atmosphere causing climate change. It is considered likely that with continued growth, the aviation sector will contribute a greater share of anthropogenic climate altering forces (Macintosh, & Downie, 2008).

The aviation industry faces increasing pressures to address environmental concerns. These pressures are mainly legislation attempting to make the polluter pay (Morrell, 2007). Perhaps these pressures are felt the most in the EU where in July 2008 the European Parliament decided that air transport would be included in the European Emissions Trading Scheme. The repercussions to the industry are not yet known because the trading scheme will not take effect until 2012 or so (Anger, 2007).

By increasing global connectivity, aviation has many social and economic benefits. It has a downside as well. Negative effects of air transport include greenhouse gas emissions, noise emissions, social disturbances and economic changes (Kutz, 2008).

The topic of aircraft fleet composition as it relates to environmental impacts is not covered extensively in the literature, but it may have political applications as the aviation industry becomes increasingly regulated for environmental impacts. Current literature on aviation's environmental impacts relates to how much fuel is used or emissions produced for individual flights or the industry as a whole. The intermediate analysis of how a mixture of aircraft affects the environment is not currently covered.

For example, it is common to use a carbon calculator to see how much carbon is emitted for a passenger on a flight or to see figures on what part aviation plays in anthropogenic climate change. However, it is not common to choose an airline based on the fact that its fleet has less overall impacts or perhaps more palatable impacts than another airline. The approach in this paper is to research environmental impacts associated with different aspects of air travel, then apply those impacts to aircraft type and compare between types of aircraft and route networks to see how fleet composition changes the type of, and intensity of environmental impacts.

Multiple fields benefit from this type of research. Political applications for this type of analysis may include a knowledge base for policymakers that regulate the aviation industry. The topic also finds overlap with airlines constant search for increased efficiency. Additionally, the study contributes to ever-growing bodies of knowledge regarding the natural environment and commercial aviation.

Literature Review

Environmental Impacts of Aircraft Fleet Management

Aviation is a mode of modern travel with well-studied environmental impacts and management strategies. These fields can be, and are, blended in the literature relating to aviation. Journals that are particularly useful for this aviation-environment study include the *Journal of Air Transport Management, Journal of Transport Geography, and Transportation Research*. In order to determine how decisions in choosing aircraft type relate to environmental impacts in emissions and noise, literature is reviewed relating to the environmental impacts of air travel, management practices of airline fleets, and specific literature on the topic itself. The ultimate goal is to answer the question of how various criteria used in choosing an aircraft type for a fleet impacts the environment.

I. Environmental Impacts of Air Travel

The environmental impacts of an aircraft can be broken down into three components of its life cycle: manufacturing, operations, and disposal. Not much research literature has focused on manufacturing impacts, though proponents of using lifecycle analyses have done some investigation (Facanha & Horvath, 2007; Lee, Ma, Thimm, & Verstreten, 2008). A vast majority of the literature focuses on the operational impacts. The main categories of operational impacts are greenhouse gasses, noise, and effects of airline fleet management decisions such as type of route network. Aircraft disposal is the opposite of operational impacts as it is sparsely covered by scholarly literature (Babisch et al., 2009; Facanha & Horvath, 2007; Lee, Ma, Thimm, & Verstreten, 2008; Simpson & Brooks, 1999).

Manufacturing impacts

Before an aircraft ever carries any passengers or cargo, it creates environmental impacts. One of the few contributors to literature on manufacturing impacts is a small group of authors who advocate for looking at all possible environmental impacts of the transportation and aviation sector including manufacturing impacts. Theses sources point out that the impact from aspects other than operations is much lower in aviation compared to land vehicles (Chester & Horovath, 2009; Facnha & Horovath, 2007).

Lifecycle analyses, which include production, as well as disposal impact studies, have been completed for the component materials in aircraft. The manufacturing stage is important to consider because design and manufacturing decisions determine ninety percent of the costs of an aircraft throughout its lifecycle (Simpson & Brooks, 1999). Modern airliners are mainly constructed with three materials: aluminum alloys, titanium alloys, and fiber reinforced polymers. These materials are used because they are strong, heat resistant, damage resistant, and lightweight. Strength to weight ratio is extremely important. The lightweight properties of these materials are what allow aircraft to reach modern levels of efficiency (Immarigeon et al., 1995; Williams & Starke Jr., 2003).

There are many materials used in manufacturing a modern airliner, but one of the staples is aluminum. It is not only the current aircraft industry standard, but has been the standard since roughly 1930 (Starke Jr. & Staley, 1996; Williams & Starke Jr., 2003). Though aluminum may offer huge operational benefits, it is generally much more energy and resource intensive to produce than other metals such as iron or steel. Furthermore, due to the large energy input required for producing aluminum (recycled or new), the source of energy is a large consideration for an environmental impact analysis, for example, geothermal versus coal produced energy (Cáceres, 2009).

Titanium alloys are commonly used in engines. Titanium alloys were generally about one percent of aircraft weight in 1950s era jets but have grown in use to about ten percent in 1980s/ 1990s generations of jets. In some military aircraft, the material has accounted for up to ninety-five percent of aircraft weight. In currently produced airliners such as the Boeing 777 and Airbus A380, much of the increase in titanium use comes from the landing gear (Immarigeon et al., 1995; Williams & Starke Jr., 2003). Titanium, like all metals is very recyclable. The largest environmental issues come from new production. Mining involves toxic materials when extracting metals from ore as well as large energy inputs (Norgate, Jahanshahai, & Rankin, 2006).

A material in aircraft that is gaining popularity, and may eventually make up over half the materials used on aircraft, is carbon fiber reinforced plastics (Soutis, 2005). Little has been studied about the environmental impacts of its production. It is known that when produced, there is a potential release of nano-fiber dust. The smaller the particulates, the more likely the dust is to interfere with chemical or biological processes. Nano-fiber dust is so variable in its interactions with the environment that a single characterization of its impact cannot be stated. It has properties of both small and large particulate interactions (Genaidy, Sequeira, Rinder, & A-Rehim, 2009; Helland et al., 2008).

Operational impacts

Literature relating to the operational impacts of aviation is much more extensive than literature about aircraft production. Among the impacts, emissions and greenhouse gasses are probably the most comprehensively studied. Other environmental impacts from operation include solid waste (from things such as in-flight meals), hazardous materials and their disposal, noise emissions and other community related impacts. In fact, one study found that there were 500 kilograms of solid waste produced per flight. These impacts are partially dependent on an airline's policies and strategy. Policies that can affect impacts include aircraft operational decisions. One example is if the auxiliary power unit on the aircraft is used or if the aircraft is hooked up to ground power from the airport when an aircraft is at the gate. Operational decisions could also include choices on what is used for in-flight meals (Moharamnejad, & Azarkamand, 2007).

Hub-and-spoke route networks became an airline strategy around the time of industry deregulation in the United States due to its route network efficiencies. Traditionally, hub operations involve aircraft flying from spoke airports to a central location, the hub airport, to arrive at the same time. Passengers can then connect through to flights outbound to different spoke airports before the bank of flights departs. This is opposed to point-to-point networks where all city pairs are connected. Each route strategy creates environmental costs (Nero & Black, 1998).

For an individual passenger, point-to-point is more efficient. However, overall it is more efficient to use hub and spoke since fewer flights are used to move all passengers to where they are going. To move passengers or cargo between all city pairs with point-to-point with five cities would require ten flights where as hub and spoke would require four flights. Any passenger not going to or from the hub city would need to connect at the hub airport (Nero & Black, 1998).

These environmental costs are concentrated in host communities of the hub airports. The environmental costs include airside and landside congestion, waste, emissions, noise, and unproductive land surrounding airports. Congestion is both from a larger number of people trying to access the airport than if it were a point-to-point airport and aircraft congestion on the ground and in the air from the increased number of aircraft movements in the area. Emissions and noise are also related to the increased number of flights. Heavy use of the airport also promotes land surrounding the airport to be used for things such a parking lots or storage, which monetarily devalues the land. These impacts are external to the finances of airlines, who are the ones deciding what type of route network to use (Nero & Black, 1998).

Another route network effect on environmental impact is that short haul air travel has a higher environmental impact per mile than long haul. This is because a larger percentage of the flight is spent during the departure phase than at cruise. The departure phase, takeoff and ascent to cruise altitude burns more fuel than cruise or descent. It is also due to the fact that short haul aircraft tend to be older and less efficient (Chapman, 2007).

Possibly the most studied aspect of environmental impacts from aircraft is the emissions from use. Aviation as a form of transportation has increased significantly in the second half of the twentieth century. It has also become much more efficient; some of the greatest airline efficiency gains came in the 1990s. Growth outpaced efficiency gains and emissions overall increased for aviation (Macintosh & Wallace, 2009).

The largest contributors to climate change in aviation emissions are carbon dioxide (CO_2), nitrogen oxides (NO_x), particulates, sulphur oxides (SO_x), and water vapor (H_2O). Aviation's contribution to climate change in 2008 was calculated to be in the region of three to eight percent. This is a minor contribution compared to industries such as electricity generation or even agriculture (Lee et al., 2009; Macintosh & Wallace, 2009).

Particulate or soot emissions are most visible due to the black carbon emitted. Black carbon emissions come from combustion. The more complete the combustion the less black carbon is emitted. Black carbon is typical of transportation emissions including aviation and is found around airports. Most of the time, black carbon pollution around airports is concentrated around the runway and caused by aircraft departures (Dodson, et al., 2009).

Jet engines emit the most at high power settings, such as during departure, though actual emissions depend on operating techniques and type of engine used. However, diesel combustion is a large producer of black carbon, and airport service equipment often runs on diesel. In comparison to diesel, jet engines burn much cleaner. Additionally, airports are generally in the vicinity of major roadways that also contribute gasoline and diesel emissions (Dodson et al., 2009; Lukachko, Waitz, Miake-Lye, & Brown, 2008).

Black carbon can be carried long distances and stay suspended in the atmosphere affecting places far from the source. It also makes specific contributions from aviation difficult to monitor. In the atmosphere, volatile particulates continue to form as much as days after due to mixing with other components of the atmosphere (Dodson et al., 2009; Lukachko et al., 2008).

Carbon dioxide is another greenhouse gas emitted by aircraft. CO_2 emissions from aircraft are very small compared to other CO_2 emissions sources. However the impact from aircraft is much greater due to the fact that much of it is emitted in the upper atmosphere (Chapman, 2007; Olsthoorn, 2001). It was found that with nitrogen oxide emissions, the amount of impact from emissions is partially dependent on factors such as aircraft location and altitude. Emissions are heaviest and most widespread globally at ten to twelve kilometers in altitude (Köhler et al., 2008).

Water emissions impacts prove one of the most tricky to pinpoint. Contrails are one of the most uncertain impacts from aviation but it is generally assumed that they contribute to global dimming. Contrails are formed from two emissions of jet engines, water and soot. The water condenses on soot to form ice crystals. In certain conditions this leads to full cirrus cloud formation (Chapman, 2007; Wong, & Miake-Lye, 2009).

While carbon or ice particulates may be visually noticeable, noise from aircraft is an audible signature of aviation. Communities around the world are bothered by this noise and there is extensive study of human physiological effects, as well as economic effects on home prices (Babisch et al., 2009; Clarke, 2003; Nero & Black, 1998).

Overall, the noise level of aircraft decreased significantly during the last thirty years of the twentieth century. Technological improvements in aircraft, especially in engine technology, facilitated this reduction in noise emission per aircraft. Engine technology has improved noise per unit of thrust, though recent generations of aircraft engines do not have the same substantial gains over previous generations (Clarke, 2003; Moharamnejad & Azarkamand, 2007).

As engine technology plateaus, there are increasing opportunities for more progress from noise abatement procedures. Noise abatement procedures are becoming more highly tuned in terms of technology and know-how. Aircraft guidance technology increased with the advent of systems such as Area Navigation and Global Positioning Systems allowing more precise following of the procedure. Studies of neighborhoods surrounding airports have given insight into what areas are most sensitive and need to be avoided as well as other considerations, such as the cost and human impacts associated with aircraft. Noise can be diluted throughout an area by using more runways for a given number of aircraft movements. This method is complimentary with the use of enhanced navigational aids and abatement procedures (Babisch et al., 2009; Clark, 2003).

One item under debate is the effect of increased aircraft movements at an airport on noise. Some consider it a major cost to the surrounding area while others dismiss it as only one part of a complex issue. One account is that noise level would only increase three decibels with a doubling of air traffic. Either way, noise pollution does not always match greenhouse gas emissions so it is an issue that needs to be addressed separately. High noise pollution is not necessarily correlated with high greenhouse gas emissions (Babisch et al, 2009; Nero & Black, 1998).

Disposal/ scrapping impacts

Little literature exists on the end of aircraft operational life. There are definitely environmental impacts associated with aircraft scrapping. However, emissions from end-of-life are very small when compared to operational emissions (Facanha, Horvath, 2007). This could be because the lifespan of an aircraft is often over thirty years, emphasizing the operational aspects (Lee et al., 2008).

A component material of modern aircraft, aluminum, has a well-developed second-hand industry. Secondhand aluminum is of good quality and high value creating a large market incentive to recycle aluminum. The main environmental consideration with aluminum recycling is greenhouse gas emissions. Greenhouse gas emissions are much lower for recycling than for primary production. Emissions are partially dependent on what is made with the recycled material. For example, rolling out aluminum to produce foil requires a large amount of energy (Dahlström & Ekins, 2007).

Carbon fiber is currently being recycled and used in non-load bearing components. Unlike aluminum, second hand carbon fiber is not trusted as a high quality material. Research is underway to figure out how to recycle it so that it retains structural integrity and can have greater use including in major structural components. This research is partially driven by the high price of new carbon fiber. It is predicted that second-hand carbon fiber will become a much larger industry as more and more things are manufactured from carbon fiber (Marsh, 2009).

II. Management Practices for Aircraft Fleets

In order to understand how management decisions affect the environment, it is important to know how decisions can be made. Literature relating to how aircraft fleets are used and managed centers around airlines. There are other ownership and management models, but they are not covered as extensively. Decisions relating to aircraft disposal in this section are based on the aircraft owner rather than the business practices of second hand part retailers or the recycling industry since the thesis topic focuses on decisions relating to active aircraft fleets, not mothballed fleets.

Aircraft Acquisition

The analysis used by airlines to make decisions on which aircraft to purchase are very involved due to the complexity and heavy consequences of the decision. The goal in aircraft selection is to choose the aircraft that will be most profitable and best fit the long-term route structure. Airlines need to take into consideration their route networks, possible future route networks, and outcomes of negotiations with manufacturers. This process can take less than a year for commuter airlines, but take much longer for major airlines. Larger airlines use a longer timescale for aircraft lifespan (Cunningham, Williamson, & Wood, 1984).

There are multiple techniques for choosing aircraft types for a fleet. These techniques are not exclusive and can be used for the same evaluation in either airline or other types of fleets. One technique is to use a list of criteria while another is to use a model that simulates operations. This second method puts different aircraft through their paces before any real metal flies the routes (Seymour, 1999; Yao, Ergun, Johnson, Schultz, & Singleton, 2008).

Regarding aircraft acquisition, the president of an airline is usually the one to make the final decision with the executive vice president also sometimes making decisions depending on the airline. Operations, finance, and maintenance divisions of airlines usually have the most say in type of aircraft selected. Airlines can also seek input from consulting firms (Cunningham, Williamson, & Wood, 1984).

Operations

For airline operations, the size of aircraft used and frequency of service provided on a route is a result of a highly complex blend of factors. Among others, economics, airline strategy, route distance, airport characteristics, passenger demand as well as demographics all influence airline routes in terms of frequency and size of aircraft used. The outcomes of these influences have been studied in the U.S. (Pai, 2009).

Economic factors can include things such as pilot salary (higher salary for heavier aircraft), economics of scale incurred with larger aircraft, market competitiveness involved with more frequency, and use or ownership of regional airlines. This ties in with airline strategy as airlines are trying to maximize profit (Givoni & Rietveld, 2010; Pai, 2009). Airline strategy also considers what market and operational strategies airlines use such as being a low cost carrier versus a regional airline. Hub and spoke airlines and low cost carriers have larger aircraft size and high frequency while regional airlines still have a high frequency, but use smaller aircraft (Pai, 2009).

Route distance and airport characteristics can limit the type of aircraft capable of serving a route, or skew the economics in favor of a certain frequency and aircraft size strategy. The result of this is that longer distance routes have lower frequency with larger aircraft size. Longer runway lengths are correlated with higher frequency and larger aircraft (Pai, 2009).

Population and demographic characteristics help determine whom the passengers are that airlines need to cater to as well as the potential market. Some characteristics of this are that, in the US, a higher income market, or larger population result in higher frequency and larger aircraft. A market with more managerial level staff, people who have a high value for time in a location's workforce, results in higher frequency with smaller aircraft. The high frequency may be due to airlines catering to people whose time is worth a lot. A larger proportion of the population below the age of 25 also results in higher frequency with smaller aircraft. This demographic may represent families with children and college students who travel a lot. Another human element of demand is temporal scale. For example, more people will want to travel over spring and summer school vacations (Pai, 2009).

Another way an aircraft fleet can be organized and utilized, other than for an airline, is through fractional ownership programs. This is where owners buy into a fleet in order to be able to use aircraft time whenever they want. A company that dispatches the aircraft when and where needed manages the aircraft (Yao et al., 2008).

This method is increasingly popular compared to other fleet types. Businesses or individuals can outright own aircraft or own an individual aircraft with other stakeholders. The problem with these systems is they often cost more and do not have the technical expertise of firms dedicated to aircraft management (Yao et al., 2008).

One concern as aircraft approach the end of their operational life is safety. Aircraft beyond their design service life are often operated by airlines that have less experience. At the same time, knowledge and data about specific aircraft, important in safety as well as reducing time and cost, is often incomplete by aircraft phase-out due to the length of an aircraft lifespan and complexity of aircraft (Lee et al., 2008; Simpson & Brooks, 1999).

Disposal

Many aircraft in the world airline fleet are operating beyond what they were designed for. Aircraft age in numerous ways – in terms of how old they are, how long they are designed and certified to last, and relative efficiency and competitiveness in the environment they operate. Owners and operators try to get the aging processes to end simultaneously. It is generally the competitiveness of the aircraft in the marketplace that is the limiting factor that causes managers to get rid of an aircraft. One tool fleet managers can use is modifying or overhauling of aircraft to try to change the aging process so that aircraft arrive at obsolescence of all three types of aging at once (Simpson & Brooks, 1999). Government regulation cannot always sway disposal decisions because of the aging processes in aircraft. For example, phase-out of noisy aircraft types in

Australia was attributed to end of the aircraft lifecycle and international issues rather than a noise tax imposed on those models (Bibisch et al., 2009).

III. Environmental Considerations in Aircraft Fleet Management

An airline management decision discussed with operational impacts is using a higher frequency of smaller aircraft verses a lower frequency of larger aircraft on a route to provide a specific number of seats. The trend is that airlines have been increasing frequency and using smaller aircraft as the industry becomes less regulated. The explosion of regional jets use during the 1990s is a large reason for the increase in frequency and decrease in size, especially in hub markets (Babikian, Lukachko, & Waitz, 2002; Givoni, & Rietveld, 2010).

A route that is short haul and high density has the option of frequency versus size. Otherwise, range considerations and/ or lack of demand constrains what aircraft can be used. On one of these short and fat routes, increasing aircraft size and decreasing frequency to provide the same seat capacity would improve overall greenhouse gas and noise emissions, but at the same time concentrate emissions impacts. Overall the environment would benefit from changing to a lower frequency, larger aircraft size system (Givoni & Rietveld, 2010).

The areas surrounding airports would have worse air quality from fewer larger jets. The advantage of larger jets comes with fuel consumption per passenger, especially while in the cruise stage of flight. Fuel consumption is directly tied to greenhouse gas emissions (Givoni & Rietveld, 2010).

Further support of this theory is that environmental impacts of large wide body aircraft are sometimes overestimated since parameters for analysis are usually based on wide bodies traveling long haul routes. For example, takeoff weight would be much higher for a long haul flight due to increased fuel load but modeling does not necessarily correct for that. This means that models may simulate a wide-bodied aircraft taking off with fuel and other provisions for a long distance flight, but then only flying a few hundred miles in the simulation (Givoni & Rietveld, 2010).

Long haul and large aircraft also tend to be the first to benefit from new technologies. For example, high bypass turbofan engines were first widely used on wide-bodied aircraft more than ten years before they became common on smaller aircraft.

These engines are much more efficient than low bypass turbofan or turbojet engines (Babikian, Lukachko, & Waitz, 2002). Another technological improvement is the use of lighter composite materials, now in major use on large aircraft, but they do not make up major components of smaller aircraft (Soutis, 2005).

Other reasons for the wide consensus that larger aircraft have less of an impact relate to noise emissions and infrastructure use. How loud and intrusive people perceive aircraft noise is more closely linked to the decibel level an aircraft emits rather than the frequency of flights passing through the area. Despite this fact, it is possible that fewer larger aircraft would have a lower overall noise level (Givoni & Rietveld, 2010). Smaller jets use some of same amount of airport infrastructure as larger aircraft, but carry fewer seats. Infrastructure use is the same for number of slots, same for air traffic control workload, and generally the same number of gates used (Pai, 2010).

Research also exists on the relationships between airport management and environmental factors as well as airport management policies and how they influence airline's operating behavior. Decisions made by airports can be with either physical infrastructure or policy and can provide constraints or expansion opportunities for airlines (Goetz & Graham, 2004; Takebayashi, 2011). Increasingly, environmental concerns are among factors considered by airport authorities (Graham & Guyer, 1999).

Conclusions

Though the literature has its gaps, such as with aircraft disposal, aviation and the environment is a well-studied topic. It is more extensive than simple environmental analysis because of the direct tie between aircraft and network efficiency and environmental impacts. The more efficiently a fleet can deliver its payload, the less environmental impacts there are. The two key environmental impacts that keep recurring in the literature are greenhouse gas emissions and noise emissions.

Greenhouse gas emissions seem to be more of an issue for scientists, domestic, and intergovernmental policy makers. Due to the direct relation to fuel efficiency, managers of fleets make decisions relating directly to greenhouse gas emissions even though they have an indirect concern with the subject. Noise emissions are important to scientists, domestic, and intergovernmental policy making groups but also have direct consequences for operators and managers of aircraft. There is not as direct a tie with noise as there is to fuel efficiency. The technologies and procedures for noise abatement are somewhat independent and specific to aircraft noise. It seems reasonable to focus on how criteria in choosing aircraft affect greenhouse gas and noise aspects since they are real-life concerns.

Methods

Methods to Study Trends Between Aircraft Fleet Makeup and Environmental Impacts

Objectives

The goal of the thesis is to determine the relationship between aircraft fleet makeup and environmental impacts. Two key questions are, does a fleet composed of more wide body aircraft tend to have fewer environmental impacts than a fleet with more narrow-body aircraft? Are hub-and-spoke route structures more environmentally friendly than point-to-point networks?

Document based research from both primary and secondary sources were used to answer the research question of how various airline fleet makeups have different environmental impacts. Secondary documents, especially peer-reviewed journals, were used to determine the relationship between fleet composition and environmental impacts.

In order to establish a relationship between the composition of aircraft fleets and environmental impacts four analyses were conducted. The results of the analyses were compared among airlines. These were airline fleet's fuel consumption, exhaust emissions, noise emissions, and infrastructure congestion.

Description of Methods

In order to keep the analysis at a manageable level, a snapshot in time of fleet compositions for eight airlines was taken for the first quarter of 2010. Airlines were chosen that have a varied fleet composition. Airlines that have a variety of aircraft types are desirable for analysis so comparisons can be made. In other words, without variation in fleet within airlines and between airlines, the analysis would simply be on environmental impacts from one type of aircraft. The airlines used in all types of analyses are among the five legacy carriers. These five were American Airlines, Continental Airlines, Delta Airlines, United Airlines, and US Airways. Airtran Airways, Federal Express, and United Parcel Service were used in some but not all of the analyses. During the first quarter of 2010 Trans World Airlines and American Airlines had fully merged into American Airlines, Northwest Airlines and Delta had merged and were operating as

Delta Airlines, but Continental Airlines and United Airlines had yet to merge and were still separate entities.

The independent variables used in analysis were fuel use, engine exhaust emissions, noise emissions, and infrastructure congestion. The sources for each variable are described below.

Fuel consumption

The first way environmental impact was measured was through fuel consumption. Aircraft fuel for each model of aircraft was derived from Research and Innovative Technology Administration, Bureau of Transportation Statistics T2 data "US Air Carrier TRAFFIC and Capacity Statistics by Aircraft Type[1]."

Total gallons were added for each aircraft type within each airline, along with available seat miles, available ton-miles and aircraft hours ramp to ramp. From those sums, gallons of fuel per available seat mile, available ton-miles (cargo) per gallon, and gallons of jet fuel per hour were compiled. This resulted in values for each aircraft type within an airline. Averages were then derived for wide body and narrow body aircraft within an airline and airlines as a whole for comparison. See Appendix 2.

Exhaust Emissions

A preliminary comparison was calculating exhaust emissions for carbon dioxide from the gallons of fuel used. The conversion rate used was 9.57 kg CO_2 per gal of Jet A fuel (Energy Information Administration, 2011). The conversion factor will be used with the fuel analysis.

The main analysis used the ICAO Simple Approach for emissions inventories. This analysis calculates carbon dioxide ($C0_2$), hydrocarbons (HC), nitrogen oxides (NO_X), carbon monoxide (CO), and sulphur dioxide (SO_2). This formula is the number of landing and takeoff cycles for an aircraft over the first quarter of 2010 times the emissions factor provided by ICAO (International Civil Aviation Organization, 2007). It is expressed as:

[1] The fuel analysis excludes aircraft smaller than the 717, DC-9-40, and any fuel used by Continental to fly 777s to the Latin America sector due to lack of usable data from the Research and Innovative Technology Administration.

Emissions type x = $\sum$ (number of landing and takeoff cycles) (emissions factor for emission x)

Total flights from an airport came from the T-100 dataset. The total number of departures performed for each aircraft type within each airline during the first quarter of 2010 were summed then multiplied by the emissions factors for each type of emission. The result was the total emissions from each aircraft type. Narrow body and wide body emissions were also aggregated for comparison. Number of seats offered is the averaging value resulting in emissions per seat for single and twin aisle aircraft for each airline. One issue with the Simple Approach to emissions inventories is that it tends to overestimate total emissions. This was not an issue since the emissions are being compared across fleets rather than being used as a stand-alone number (International Civil Aviation Organization, 2007; Kurniawan & Khardi, 2011).

Noise Emissions

Aircraft type and engine type were researched through the FAA Registry or the airline's website. The airlines used were American Airlines, Continental Airlines, Airtran Airways, and United Parcel Service because specific engine types are reported and comparisons can be made between hubs and spokes. Effective perceived noise level in decibels (EPNdB) was derived from FAA Advisory Circular 36-1H for each aircraft type. EPNdB takes noise duration and accounts for irregularities in the raw decibel level measurement (Federal Aviation Administration, 2002).

The takeoff and landing noise levels were added together since it was assumed that for each takeoff there is a landing from the same type of aircraft at a given airport. If there was a possibility of two different engine types for an aircraft the noise levels were averaged out. For example, American MD-80s either used JT8D-217A, JT8D-217C or JT8D-219 engines, -217A takeoff EPNdB is 92.0 and -217C takeoff EPNdB is 91.5 and -219 takeoff EPNdB is 90.8. A value of 91.75 EPNdB was used for American's MD-80s. Where there were values for multiple flap settings, the higher flap setting was used. Where there were values for multiple maximum takeoff and landing weights, the higher weights were used. Higher flap settings and weights generally result in higher sound levels. Results can be seen in Table 1 (American Airlines, 2011; Continental Airlines, 2011; and Noise Division AEE-110, 2001).

Table 1: Engine Type, Takeoff, Landing, and Total Decibel Levels for Each Aircraft Type Within Selected Airlines

Airline Aircraft type	Engine Type	Takeoff EPNdB	Landing EPNdB	Total EPNdB
American				
MD-80	JT8D-217A/C; JT8D-219	91.4333	93.7	185.1333
737-800	CFM56-7B24/3	88.6	96.5	185.1
757-200	RB211-535E4B	85.7	95.2	180.9
767-200/ER/EM	CF6-80A	92.8	101.7	194.5
767-300/300ER	CF6-80C2B6	91.1	98.4	189.5
777-200/200lr/233lr (ER)	Trent 892	94	99.5	193.5
Continental				
737-300	CFM56-3B1	87.5	100.1	187.6
737-500	CFM56-3B1	87.3	100	187.3
737-700/700LR	CFM56-7B24	88.6	96.1	184.7
737-800	CFM56-7B26	85.6	96.6	182.2
737-900	CFM56-7B26	87.2	96.4	183.6
757-200	RB211-535	88.1	99.6	187.7
757-300	RB211-535E4B	88.4	95.4	183.8
767-200/ER/EM	GECF6-80C2B4F	88.5	96.5	185
767-400/ER	GECF6-80C2B8F	91.2	98.7	189.9
777-200/200lr/233lr (ER)	GE90-90B	91.3	97.8	189.1
Airtran				
717-200	BR700-715C130	82.1	91.6	173.7
737-700/700LR	CFM56-7B22	86.3	95.9	182.2
UPS				
757-200	PW2040; RB211-535E4	88.5	96.65	185.15
767-300/300ER	CF6-80C2B6F	90.9	98.5	189.4
A300B/C/F/-100/-200	PW4158	93.1	101.9	195
MD-11	CF6-80C2D1F; PW4462; PW4460	94.5333	104.1333	198.6666
747-400F	CF6-80C2B1F	99.7	101.4	201.1

The total EPNdB was then multiplied by the number of departures from the largest hub airport and the largest large spoke airport using the T-100 dataset. Miami International was used for UPS since it is the largest middle sized hub when applying the FAA hub classification to tons of cargo. The average EPNdB per departure was also calculated by dividing the total number of departures for an airport over the total EPNdB for all departures.

The hub for American was Dallas/Fort Worth and the spoke was San Antonio. The hub for Continental was Houston George Bush and the spoke was Austin-Bergstrom. The hub for Airtran was Atlanta Hartsfield and the spoke was Greater Rochester. The hub for UPS was Louisville and the spoke was Miami.

Infrastructure Congestion

Infrastructure congestion was measured through flight delays since airside congestion is more directly related to aircraft fleets than landside congestion. To examine airport delays, hub and large non-hub airports were first defined, identified, and then delays between them were compared. In order to determine hub airports, two methods for identifying were used. Those methods are the FAA method and a modified Herfindahl-Hirschman Index (HHI); both are described below. These two methods of identification were to minimize the flaws and assumptions that do not match the real world for each individual method. Airports that fit both hub identification methods were classified as hubs. However, even after employing both the FAA and the HHI methods, there was discretion used to re-categorize airports that seemed to be mislabeled. For example, Continental had one hub, Houston George Bush Intercontinental Airport (IAH), using both methods. However, the airline clearly had another hub at Newark Liberty International Airport (EWR). IAH had about 32 percent of the passenger traffic and EWR handled about 25 percent of Continental's passenger traffic, the next largest airport in Continental's system was CLE at around 4 percent.

As noted above, the first method is the FAA method. This is to simply use a percent of total passenger traffic for each airport within an airline. Three categories of hub airports defined by the FAA start with .05-.25 percent of passenger traffic within a network called a "small hub," .25-.1 percent is a "medium hub," and more than 1 percent is classified as a "large hub" (Costa, Lohmann, & Oliveira, 2010).

The second method was a modified Herfindahl–Hirschman Index (HHI). The original HHI formula is HHI = ΣP_i^2. P is the market share and "$_i$" is the firm. In this study, the formula will not be applied. A simpler strategy was used to identify airports that would have fallen under the hub category with the formula. The percent of passengers through an airport in a network, the market share, was added starting with the largest market (airport) progressing towards the smallest market (airport). When the sum of the market shares reached fifty percent, all airports listed were classified as hubs. The assumption necessary for the simple strategy is that all flights are between hub airports and spoke airports (Costa et al., 2010).

Using the T-100 dataset both methods were used to find hubs for the sixteen air carriers that are required to report on time data. When one of the airports was not found to be a hub of any of the legacy airlines used for analysis, it is considered to be a non-hub airport.

Airports considered hubs were Atlanta Hartsfield, Boston Logan, Charlotte Douglas, Denver, Dallas/Fort Worth, Detroit Metro Wayne County, Newark Liberty, Fort Lauderdale-Hollywood, Washington Dulles, Houston George Bush, New York John F. Kennedy, Los Angeles, Orlando, Miami, Minneapolis-Saint Paul, Chicago O'Hare, Philadelphia, Phoenix Sky Harbor, Seattle-Tacoma, San Francisco, Salt Lake City.

The sixteen reporting carriers were Airtran Airways, Alaska Airlines, American Airlines, American Eagle Airlines, Atlantic Southeast Airlines, Comair, Continental Airlines, Delta Airlines, Hawaiian Airlines, JetBlue Airways, Mesa Airlines, SkyWest, United Airlines, and US Airways.

Data for the analysis was downloaded from "On Time Performance Data" for January, February, and March 2010 then merged into one spreadsheet for each airline. Departure delays in minutes were averaged for all departures within the time period for each airport classified as an FAA large or medium hub within each airline's system. The departure delay field also includes early departures with a negative value. The result is an average of all minutes before (negative value) and after (positive value) the scheduled time. Departure delays were compared between the airports that fit all criteria for each airline used in the hub analysis and airports that only qualified as medium hubs in the

FAA methods but did not qualify as an FAA method large hub for any of the airlines analyzed.

Once raw data was known, the next step was to research environmental impacts associated with the different ways the aircraft are actually operated for discussion. For example, airlines make decisions related to aircraft type on long haul versus short haul routes, high frequency low density versus low frequency high density, and hub and spoke versus point-to-point routing. Fuel consumption was researched along with the associated impacts of emissions including soot. Other impacts researched were noise emissions and infrastructure congestion. The objective is to make the research relevant to the real world.

From there, the environmental impacts research was applied to the actual flights and routes to see how environmental impacts of differing fleet compositions compare to each other. The idea was to use the research to assign specific impacts and severity of those impacts to a type of flight. Impacts from individual aircraft types were combined. This allows trends between aircraft types and environmental impacts to be established.

Justification of Methods

Document based research was chosen for a variety of reasons. However, the main reason is that accurate documents are accessible. Having specific quantitative information is necessary, and it would be impractical to conduct accurate observations or experiments on aircraft fleets since even the smallest of airlines cover a large geographic area. Information was needed on what routes were flown by which aircraft and how many times as well as information on fuel use and delays. The Bureau of Transportation Statistics is objective and data can generally be relied upon for accuracy. An issue was that accuracy is reliant on air carriers self-reporting. Nevertheless, the statistics are raw data and not a person’s judgment call (BTS, 2010; Denscombe, 2007).

Academic journals are also useful due to their accessibility and were used for environmental impacts research. This research centers on fuel consumption, emissions including noise, and infrastructure congestion. These are not as clear-cut as statistical data, but they are peer reviewed and thus should be credible. Journal articles have the added value of the expertise of the author(s). Measuring broad environmental impacts with all first hand data is out of the scope of the thesis due to timetable of the project and resources available (Denscombe, 2007).

Techniques relying on other people such as surveys or interviews are impractical because individuals would need to be willing and able to communicate about the topic, have the specific information on the topic, and be free of bias (Denscombe, 2007).

Analysis

The objective of the analysis of the results was to establish relationships between aircraft type and environmental impacts. Individual fleet compositions were broken down to analyze what the environmental impacts were for different segments of the fleet. Fleets were broken down into aircraft size witch roughly correlates to distance of route commonly flown (Pai, 2009). This analysis was to determine how individual aircraft type decisions affect the environment.

A broader analysis that was considered was where impacts from the type of segments flown by aircraft were aggregated into impacts of entire fleets. Fleets were compared to each other for composition and environmental impacts. This analysis was to determine how broad fleet strategies affect the environment.

Analyses were limited to a specific time period and small number of airlines due to the large volume of data related to any individual fleet. Limitations on fleet selection also come from the objective of analyzing airlines with varied fleets. Air carriers with homogenous fleets may use their aircraft in a way different from airlines with diverse fleets. The exception was Airtran, which was used in emissions analysis. Airtran had only two aircraft types that are a similar size to one another.

There were two comparisons, the first was of relationships between different types of aircraft, the intra-fleet analysis; this led to the second comparison and final product. The final product was comparison between the different fleets. The first comparison gave an indication of environmental impacts associated with type of aircraft. The second comparison gave an indication of how mixtures of different types of aircraft affect the environment.

Results

Data from the analyses was compiled for aircraft size and route structure categories within each airline or airport. In the fuel, exhaust and noise emissions analyses single and twin aisle aircraft were grouped together for comparison and in the exhaust, noise, and infrastructure analyses the differences between hub and non-hub airports were examined.

Fuel

The most basic of the results was which type of aircraft burned more fuel in an hour of operation. In overall fuel consumption for each airline, wide body aircraft burned more gallons per hour for all airlines. The results can be seen in Figure 1.

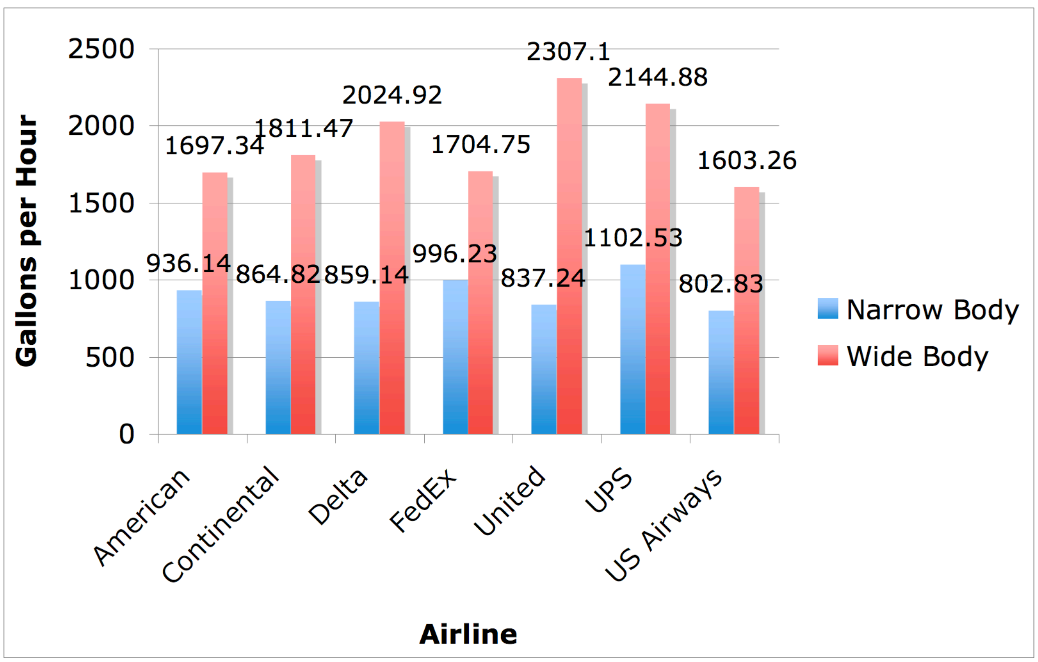

Figure 1: Gallons of Fuel per Hour for Each Airline Broken Down by Narrow and Wide Body Aircraft

Some items of note are that United had both the highest fuel burn per hour for wide bodies and the largest difference between wide and narrow body aircraft. US Airways had the lowest fuel burn for narrow bodies at around 802 gallons per hour. FedEx had the smallest difference between narrow and wide body aircraft.

Seat mile per gallon (the number of miles one seat can fly with one gallon of fuel) for wide body aircraft are higher, more efficient, for Delta Airlines and US Airways. On the other hand, American Airlines, Continental Airlines, and United Airlines all had a higher seat mile per gallon average for their narrow body aircraft. FedEx and UPS are cargo carriers so they are not included in the seat mile per gallon calculation. Differences between narrow and wide body aircraft can be seen in Figure 2.

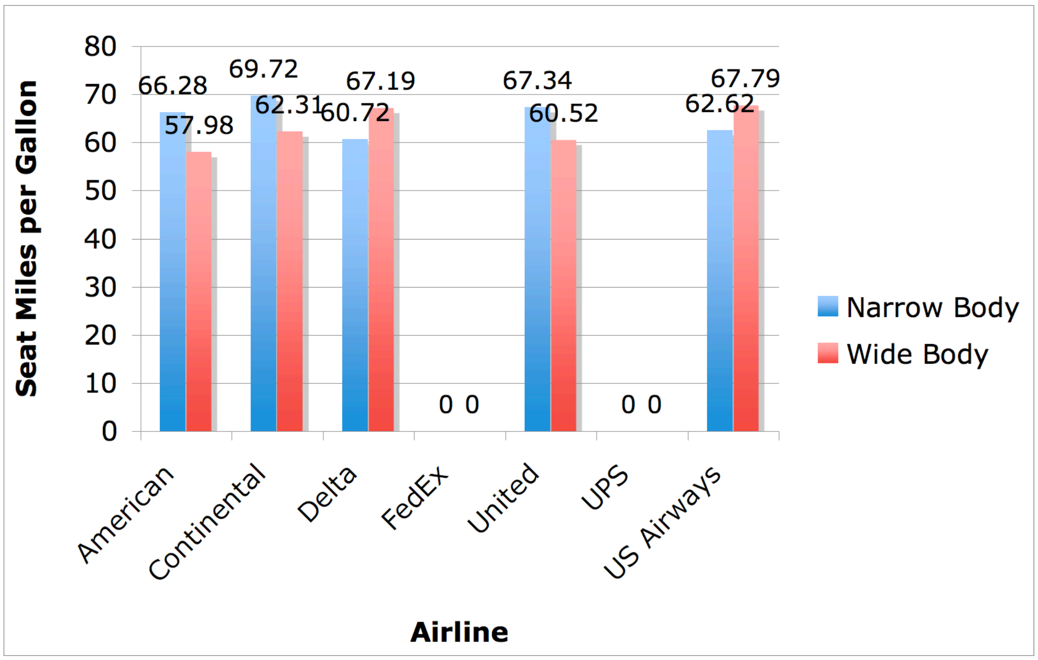

Figure 2: Seat Miles per Gallon for Each Airline Broken Down by Narrow and Wide Body Aircraft

Continental had the highest seat miles per gallon out of all the averages with their narrow body aircraft at around 69.7191. Continental narrow bodies were most efficient. The least efficient with the highest seat miles per gallon was American's wide body average at 57.983.

American had a difference of 8.27 in seat miles per gallon between single and twin aisle aircraft, followed by Continental with a difference of 7.41, and United with a difference of 6.81 in seat miles per gallon between single and twin aisle aircraft. US Airways had a difference of 5.17 in seat miles per gallon between single and twin aisle aircraft, but wide bodies averaged more seat miles a gallon. There was a difference of 6.46 in seat miles per gallon between single and twin aisle aircraft for Delta, but wide bodies also averaged more seat miles a gallon.

There is not a strong relationship between number of different types of aircraft in a fleet and seat miles per gallon for the fleet as a whole. For example, using 17 aircraft types, Delta had a fleet wide average of 63.14 seat miles a gallon. Continental used 10 types and had an average of 67.49 seat miles per gallon. US Airways used 9 types and averaged 63.77 while American used 6 types and had an average of 62.13. Finally, United used 6 types and had an average of 63.93 seat miles per gallon.

In freight ton miles per gallon, wide body aircraft had a higher average. That is wide body aircraft were more efficient with fuel across the board including with the two cargo airlines in the fuel portion of the study Federal Express and United Parcel Service. Both cargo carriers were more efficient than the passenger airlines within the wide body narrow body categorization. Averages can be seen in Figure 3.

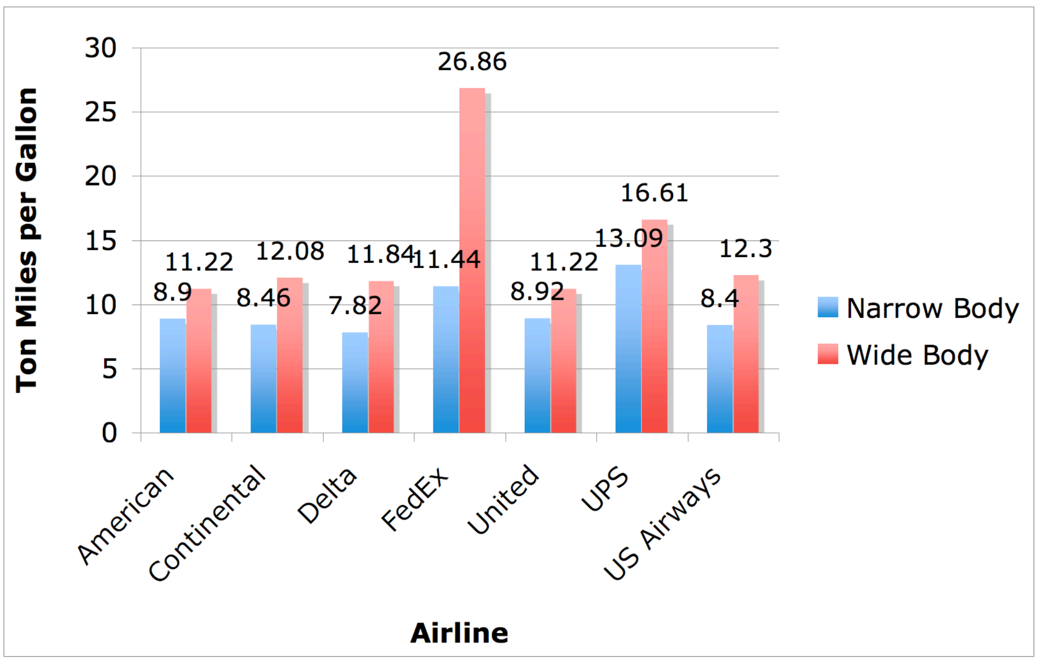

Figure 3: Ton Miles per Gallon for Each Airline Broken Down by Narrow and Wide Body Aircraft

FedEx showed the largest difference between wide and narrow-bodied aircraft at 15.42. This was followed by Delta with 4.02, US Airways with 3.9, Continental with 3.62, UPS with 3.52, and United with 2.3. FedEx also had the most efficient overall with the wide body segment of the fleet. The least efficient was Delta's narrow bodies at 7.82 ton miles per gallon.

Exhaust emissions

For almost all types of emissions, narrow body aircraft emit less greenhouse gasses per seat. Variations between single aisle (narrow body) and twin aisle (wide body) aircraft as well as between different airlines can be seen depending on the type of emission. Since the various airlines used many of the same aircraft types, variations within each emissions species are similar.

Carbon Dioxide emissions followed the trend of fewer emissions from narrow bodies across all air fleets examined. The highest emitter of CO_2 was American wide bodies, 28.5534 kg of CO_2 per seat. The lowest emitter was US Airways narrow bodies at 18.5989 kg per seat. Results can be seen in Figure 4.

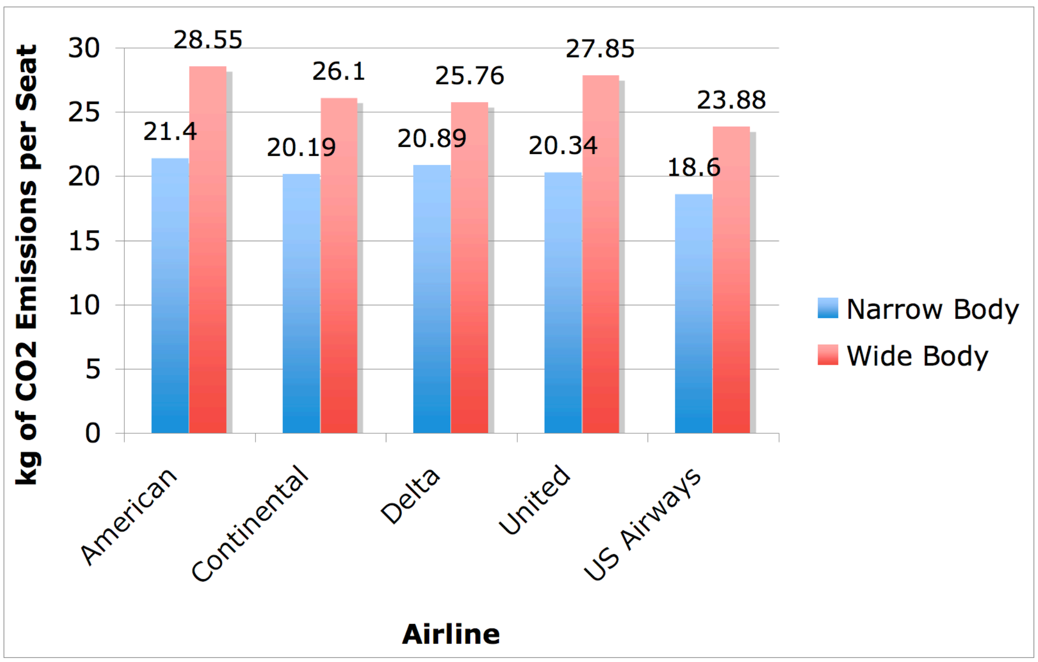

Figure 4: Average CO_2 Emissions per Seat For Narrow and Wide Body Aircraft for Each Airline

For HC emissions, twin aisle aircraft had more emissions per seat than single aisle with Delta as the exception. Not only did delta narrow bodies emit more than the wide bodies, but also Delta had the largest difference in per seat emissions between the two parts of their fleet. United single aisle aircraft averaged the least emissions at .00334 kg.

United also had the smallest difference within the fleet at .00135. The breakdown is in Figure 5.

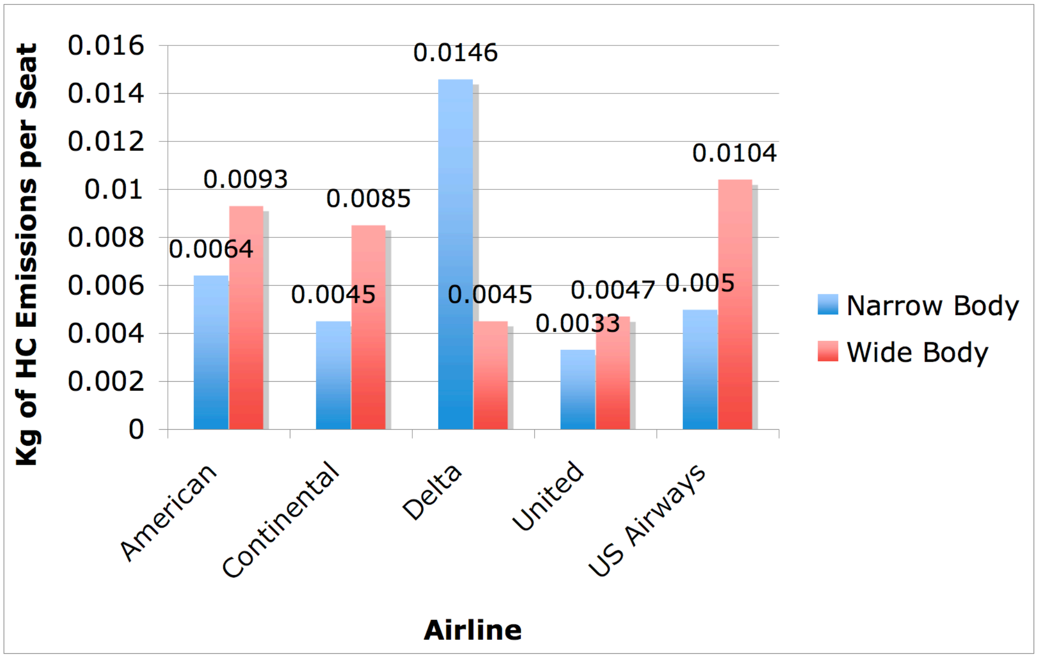

Figure 5: Average HC Emissions per Seat for Narrow and Wide Body Aircraft for Each Airline

Hydrocarbon emissions from Delta narrow bodies were more than any other average at .01462 kg per seat. The next closest per seat emitter was .0042 kg less. Contributing to this was the DC-9 fleet. The emissions factor given for DC-9s was 4.63 while most other aircraft were given a factor of below 1.

CO emissions were less per flight for single aisle aircraft with American, United, and US Airways. Twin aisle aircraft emitted less per flight for Continental and Delta. The highest average was Delta narrow bodies that emitted .07481 kg and the lowest emitter on a per seat basis was American narrow bodies at .04536 kg. Differences in emission averages were largest for American at .02298 kg and smallest for US Airways at .00364 kg. See Figure 6.

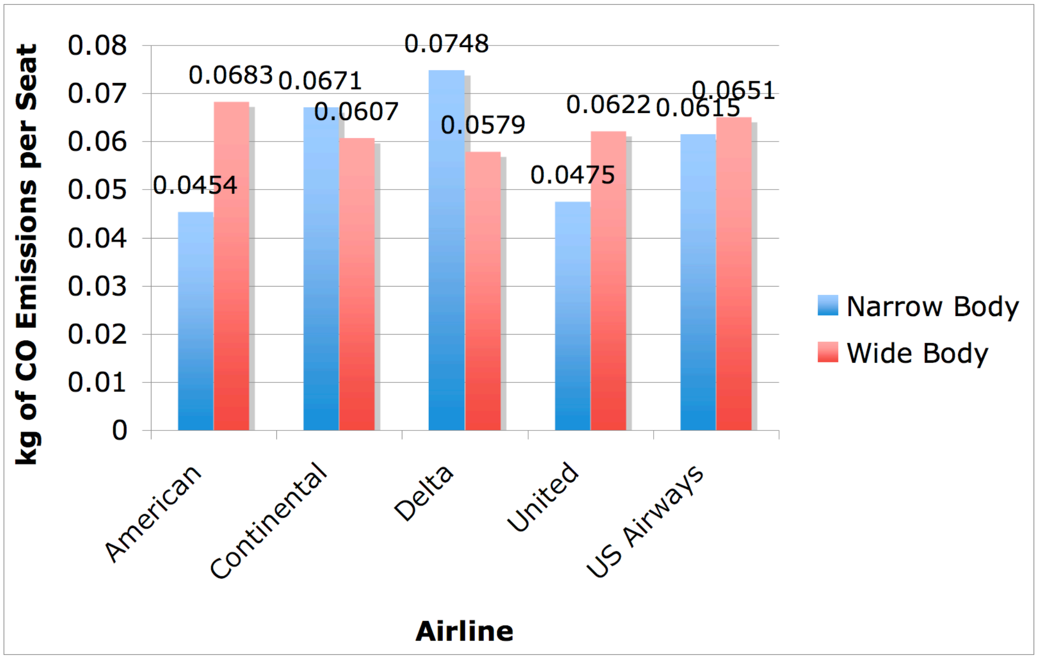

Figure 6: Average CO Emissions for Narrow and Wide Body Aircraft for Each Airline

Delta once again has its narrow body emissions inflated due to flights with the DC-9 series aircraft. Continental emitted more from narrow bodies partially due to their classic generation 737s. This is the only instance out of all types of emissions where an airline other than Delta had higher emissions on a per seat basis from narrow bodies than wide bodies. Emissions factors were high in CO for both DC-9 and classic 737.

NO_X emissions followed the trend and were consistently less for narrow body aircraft on a per seat basis. The uppermost emitting average was from American wide bodies at .16098 kg and the lowermost average was Delta's narrow bodies at .07407 kg. The largest difference within a fleet was American at .06362 kg. The most consistent fleet was US Airways with a difference of .04548 kg. See Figure 7.

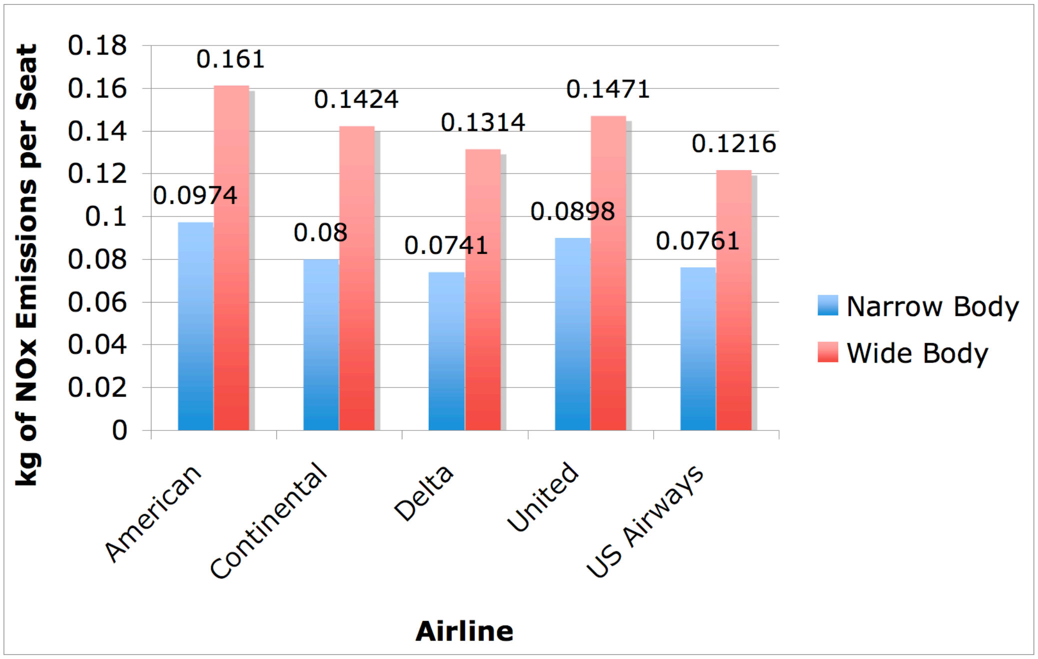

Figure 7: Average NO_X Emissions per Seat for Narrow and Wide Body Aircraft for Each Airline

SO_2 emissions were also consistently less per seat on single aisle aircraft. The highest impact came from American wide bodies at .00902 kg. The lowest impact came from US Airways single aisled aircraft, .00588 kg. The largest difference within a fleet between narrow and wide bodies was .00237 with United. The smallest difference in averages within a fleet was Delta at .00154, as seen in Figure 8.

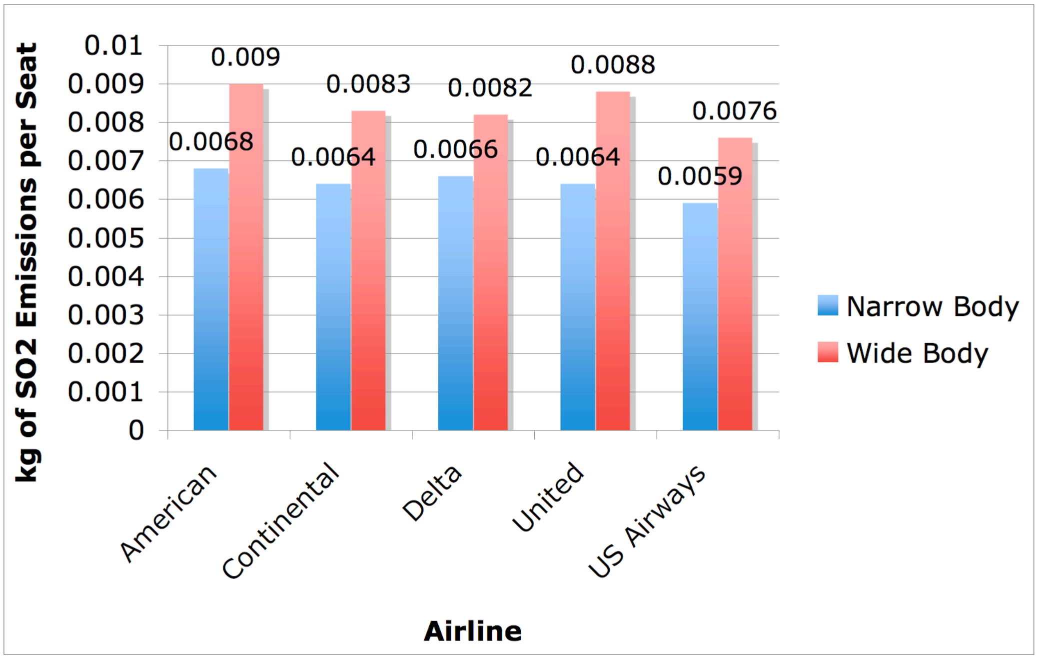

Figure 8: Average SO_2 Emissions per Seat for Narrow and Wide Body Aircraft for Each Airline

Noise emissions

For all of the airlines and airports used in the noise calculations, the hubs had a higher sound level per departure than spoke airports. American (AA) had a difference of 1.5544 decibels. Continental (CO) had a difference of 1.3391, Airtran (FL) had a difference of 4.2616, and UPS (5X) had a difference of 2.7512. The results for each airline's two airports can be seen in Table 2.

Table 2: Average EPNdB per Aircraft Movement For Hub and Spoke Airports by Airline

	Hub	Spoke
AA	186.6793	185.1249
CO	186.0353	184.6962
FL	177.9616	173.7
5X	192.1101	189.3589

Interestingly, the largest differences between hub and spoke airport EPNdB come from Airtran who has a fleet of all narrow body aircraft and UPS which has a fleet comprised of almost all wide body varieties had the second biggest difference.

For all airlines and all flights narrow body aircraft were quieter than wide body aircraft and airline average as a whole. UPS had the loudest average. The things that set UPS apart were that it had the least narrow body movements and it is the only cargo airline in this analysis. Averages for single and twin aisle aircraft are in Table 3.

Table 3: Average EPNdB per Aircraft Movement Wide and Narrow Body Aircraft by Airline

	Narrow body	Wide body	Airline average
AA	184.2892	191.5363	185.0165
CO	184.1922	188.2774	184.4768
FL	176.4766		176.4766
5X	185.15	194.7260	191.6562

Infrastructure congestion

Three hub airports were identified and 20 large spoke airports were identified for American Airlines. The Average of delays at hub airports was 13.1408 minutes while the average of delays at large spoke airports was 6.9680. The difference between hub and spoke was 6.1728 minutes. American had the largest averages for both hub and spoke delays of all airlines examined. See Table 4.

Table 4: Average Delays in Minutes for Hub and Spoke Airports in American Airlines Network

AMERICAN AIRLINES Hub Airports	Average Delay in Minutes	Large Spoke Airports	Average Delay in Minutes
DFW	10.95	SAT	6.84
MIA	16.25	SNA	2.72
ORD	12.22	RDU	7.99
		MSY	7.70
		MCI	5.62
		HNL	12.21
		TUS	7.25
		BNA	3.57
		ELP	3.11
		EGE	20.08
		RSW	4.57
		OKC	-.46
		ABQ	2.10
		TUL	3.14
		PBI	15.28
		BDL	2.76
		IND	10.57
		OGG	11.23
		OMA	3.04
		PSP	10.05
Average	13.14	Average	6.97

With Continental, two hub airports were identified and 7 large spoke airports. The Average of average delays at hub airports was 11.3238 minutes while the average of average delays at large spoke airports was 1.1931. The difference between hub and spoke was 10.1307 minutes. Continental had the distinction of the least average delay for spoke airports as well as the largest difference in delays between hubs and spokes in the route network. See Table 5.

Table 5: Average Delays in Minutes for Hub and Spoke Airports in Continental Airlines Network

Continental Airlines Hub Airports	Average Delay in Minutes	Large Spoke Airports	Average Delay in Minutes
IAH	9.09	AUS	2.39
EWR	13.56	HNL	2.99
		SNA	4.63
		SMF	3.33
		ONT	- 4.37
		SJC	1.33
		MFE	-1.95
Average	11.33	Average	1.19

In Delta's system, 4 hub airports were identified and 17 large spoke airports. The Average of average delays at hub airports was 10.5714 minutes while the average of average delays at large spoke airports was 6.9173. The difference between hub and spoke was 3.6541 minutes. Delta had the smallest difference in average delays between hub and spoke airports. See Table 6.

Table 6: Average Delays in Minutes for Hub and Spoke Airports in Delta Airlines Network

Delta Airlines Hub Airports	Average Delay in Minutes	Large Spoke Airports	Average Delay in Minutes
ATL	8.92	BDL	8.21
MSP	10.57	JAX	6.78
DTW	11.71	RDU	6.43
JFK	11.09	MKE	5.79
		IND	8.74
		SJU	5.50
		SNA	3.31
		MCI	6.61
		STL	5.63
		SAT	9.78
		RIC	6.79
		SRQ	12.14
		CMH	8.18
		BUF	11.23
		MSN	5.04
		ORF	7.01
		SMF	0.44
Average	10.57	Average	6.92

United was found to have 3 hub airports and 14 large spoke airports. The Average of average delays at hub airports was 8.4390 minutes while the average of average delays at large spoke airports was 3.7314. The difference between hub and spoke was 4.7076. See Table 7.

Table 7: Average Delays in Minutes for Hub and Spoke Airports in United Airlines Network

United Airlines Hub Airports	Average Delay in Minutes	Large Spoke Airports	Average Delay in Minutes
ORD	9.90	OGG	4.76
DEN	6.46	SNA	4.01
SFO	8.96	MSY	1.66
		OMA	2.35
		SMF	0.83
		KOA	5.83
		MCI	2.60
		BDL	1.01
		SJU	15.18
		PIT	5.66
		RNO	2.97
		LIH	2.13
		ONT	0.22
		SJC	3.03
Average	8.44	Average	3.73

With US Airways, 3 hub airports were identified and 18 large spoke airports. The Average of average delays at hub airports was 6.8015 minutes while the average of average delays at large spoke airports was 1.4798. The difference between hub and spoke was 5.3217 minutes. See Table 8.

Table 8: Average Delays in Minutes for Hub and Spoke Airports in US Airways Network

US Airways Hub Airports	Average Delay in Minutes	Large Spoke Airports	Average Delay in Minutes
CLT	8.16	SJU	12.64
PHX	3.58	RDU	4.55
PHL	8.66	JAX	-0.63
		PVD	0.94
		SNA	-1.46
		BDL	1.45
		MCI	-0.34
		BUF	-0.92
		SJC	-4.00
		ONT	-1.24
		SMF	-3.93
		IND	1.44
		STL	0.35
		MSY	1.97
		RNO	-0.29
		STT	16.12
		OAK	-2.52
		HNL	2.50
Average	6.80	Average	1.48

For all airlines, delays were larger at hub airports. Some non-hub airports analyzed had negative values indicating flights left early on average. This was not the case at any of the hub airports Average hub delays in decreasing order were American at 13.1408 minutes, Continental at 11.3238 minutes, Delta at 10.5714 minutes, United at 8.4390 minutes, and US Airways at 6.8015 minutes.

Discussion

A comparison between aircraft types within the same fleet was used to come up with the main comparison of fleet wide impacts. The main finding the analyses produced was a comparison between different fleet compositions. This is the level of comparison examined in the literature review.

Based on the literature review, two findings were expected in the results. First, it was expected that larger aircraft would likely be more efficient than smaller aircraft due to economics of scale, but have a greater concentration of environmental impacts. Second, it was considered likely to find that fleets with an even mix of aircraft size would have the least overall impacts and not have a concentration of one type of impact since appropriate aircraft can be used for specific routes.

The comparison of total amount of fuel burned is exactly what was expected. Wide body aircraft burn more gallons of fuel per hour. This does not imply anything about aircraft efficiency since it is not averaged out with any other factors. Simply, bigger aircraft burn more fuel. The analysis is a good test of the methods and confirms that they work.

The seat miles per gallon analysis netted some interesting results. In a majority of the airlines, three of five, narrow body aircraft were more efficient. This does not conform to existing data. Existing data indicates a better fuel burn for seat mile in larger aircraft and a higher fuel burn from short haul flights. Smaller aircraft are generally used on shorter flights (Chapman, 2007; Givoni & Rietveld, 2010).

The conflict with the previous literature may come from the fact that specific fuel burn per flight hour was not used; rather, total hours ramp to ramp was used. Ramp to ramp hours include time spent taxiing or holding while the aircraft is on the ground. The airport congestion analysis does conclude that more departure delays occur at hub airports and the noise emissions analysis confirms that more twin aisle departures occur at hub airports.

Reasons for a weak relationship between seat miles per gallon and fleet variety may be because of fleet age, defining variety by aircraft sub-types, or the correlation may just not exist. An example where fleet age may come into play is with Continental. During the first quarter of 2010 there were still some flights with 737-300s. This was counted as an aircraft type even though it was in the process of being eliminated from the active fleet. As of first quarter 2011, there were no 737-300s remaining in the active fleet of Continental (Continental Airlines, 2011). If aircraft types are defined by series rather than branding type (737 instead of 737-300, A320 series instead of A319, A320, A321), Delta had 10, US Airways had 6, American had 5 types, United had 5, and Continental had 4. Using this breakdown there appears to be a trend that fewer aircraft types is related to more seat miles per gallon. The exception to this trend is American.

Emissions were heavily affected by fleet age. Delta and its DC-9s were highlighted in the results section. The DC-9-30 is the oldest of DC-9 variants used by Delta during the time of analysis. This variant first flew in 1967 and is the oldest sub-type of aircraft flown by any of the carriers analyzed (Boeing, 2011).

In terms of raw numbers generated by the analysis, large differences in emission averages within a fleet between narrow and wide bodies usually relate to a high level of emissions. The high average is usually one of the highest across all of the airlines analyzed. Conversely, a small difference within a fleet usually indicates a low emitting fleet.

Another trend with regard to emissions was that wide bodies emit more on a per seat basis than narrow bodies. Results of the emissions analysis are consistent with the fuel analysis given the fact that wide bodies use more fuel per hour in all airlines and more on a seat mile basis in most airlines examined. They are also consistent with the literature, larger aircraft were found to be worse for local air quality (Givoni & Rietveld, 2010). Especially since the ICAO analysis was provided as a part of airport planning strategies (International Civil Aviation Organization, 2007).

The fact that hubs have more average noise per departure may come from either hubs having more departures from larger aircraft or more departures from older aircraft. The fact that older aircraft create more noise, but there has been a plateau in improvements was confirmed by the noise study. In the 100 to 150 seat range, the MD 80 with an entry into service year of 1980 is rated at 185.1333 EPNdB. Classic generation 737s were also louder than newer aircraft. A 737-300 and 737-500 both emit around 187 EPNdB. Next generation 737s emit in the low to mid 180s EPNdB including the 737-900, which is even larger than the 100 to 150 seat range (Clarke, 2003; Moharamnejad & Azarkamand, 2007; Noise Division AEE-110, 2001).

Age and size difference may explain why Airtran and UPS had the largest difference in noise emissions between hub and spoke airports. In the case of Airtran, there were only 717 flights into ROC. The 717 is smaller than the 737-700 and had an entry into service date around two years later than the 737. Even though Airtran has little variety in its fleet, the same factors come into play (Boeing, 2011).

In the case of UPS, the narrow body 757 is older than all aircraft types in its fleet with the exception of the A300 (Airbus, 2011; Boeing 2011). Louisville, the hub, had all aircraft types represented while Miami airport had a mix of aircraft, but not all types in the fleet.

Average hub delays in decreasing order were American, Continental, Delta, United, and US Airways. The number of hubs identified was four for Delta three for American, United and US Airways, and two for Continental. Hub delays did not match up with number of hubs an airline operates. Total seat miles flown per airline matched for some airlines but not others. In decreasing size these were Delta 45,622,148,618; American 36,843,938,455; United 28,480,007,487; Continental 22,584,528,188; and US Airways 16,577,478,659. The ratio of seats offered on narrow body to wide body did not match either. The higher the ratio the more seats are offered narrow body aircraft throughout each network. Based on the same data tables used for the emissions inventory US Airways had a ratio of 16.6046, Continental of 8.7212, American of 6.1528, Delta of 6.0633, and United of 3.0454.

What did match was that the hub airport delays matched overall departures performed for the year 2010. From the most to the least, the top 15 airports for total departures were ATL, ORD, DFW, DEN, LAX, IAH, CLT, DTW, PHL, MSP, PHX, EWR, JFK, SFO, LGA. Delays and departures also matched the seats available from the busiest airports in 2010. In descending order these were ATL, ORD, LAX, DFW, DEN, JFK, PHX, IAH, SFO, LAS, CLT, MIA, EWR, MCO, MSP (U.S Department of Transportation Research and Innovative Technology Administration, 2010).

Bigger airports have more delays regardless of the number of hubs with which an airline spreads its network out, or the size of the airline. Market size is recognized as a significant variable. Airport delays are partially external to aircraft fleet management (Santos & Robin, 2010).

Significant variables in airport delays include slot constraints in airports, rolling versus banked hubs (see Appendix 1), the way an airline internalizes delays, and the difference between how little time a route could take and the time it actually does take. The analysis of difference between scheduled and actual departure time was from a passenger perspective. In some cases, such as in Europe, the correlation between hub size and delays is “U” shaped rather than linear (Nero & Black 1998; Santos & Robin, 2010).

Conclusions

Through the four analyses there were some recurring themes. One was aircraft age. Older aircraft have larger environmental impacts. Analyses where this could be seen were emissions and noise. Another theme was that size was not always synonymous with efficiency, or synonymous with fewer impacts on a per unit basis. This is contrary to what was expected from the literature. Wide body aircraft have more impacts. The seat miles per gallon were fewer while local engine exhaust emissions, and engine noise, were more than narrow bodies.

Large hub airports experienced more noise and delays than spoke airports. This appears to be linked to more aircraft movements and more large aircraft in large hubs than in medium or small spoke airports. Congestion hinders efficiency and increases environmental impacts as evidenced by both this study and the existing literature.

An airline that performed well environmentally in the analysis was US Airways, especially the narrow body component of the fleet. The narrow body component had the lowest gallons per hour fuel consumed, fewest kilograms of CO_2 emissions per seat, fewest kilograms of SO2 emissions per seat, and US Airways had the shortest average hub delays. US Airways was not used in the noise emissions analysis.

These analyses were not enough to conclusively determine which airlines are the best or worst, they simply highlight areas where the airline had fewer and less severe impacts. For example, American wide bodies burned the least fuel per seat mile on average and FedEx wide bodies averaged the most ton miles per gallon by a wide margin.

There are a variety of characteristics that may have contributed to the performance. US Airways had the second highest variety of fleet types. This did not have a strong relationship to low impacts, but it is thought to help. From the recurring themes, the fleet is comprised of newer generation aircraft types, and single aisle aircraft had fewer impacts than twin aisle aircraft. The hubs used CLT, PHX and PHL were among the busiest, however none were in the top five in departures performed or seats available.

There are many possibilities for further study. Based on the literature review, research on environmental impacts from aircraft manufacturing or disposal is a largely uncovered area. If the study were repeated, the fuel, exhaust emissions, noise emissions, and infrastructure congestion analyses could be conducted in more depth. The exhaust emissions analysis in particular could be completed in more depth using the ICAO advanced approach with specific engine types as was done in the noise analysis. Criteria such as geography of airports served or length of flight (stage length) could be used instead of hub versus spoke or wide body versus narrow body.

According to the results, the ideal airline from an environmental impacts standpoint would have a fleet comprised of more narrow body aircraft than wide body aircraft. It would also have a young fleet using the latest generation aircraft. The route structure would be a hub and spoke system, but not with a hub based at a large airport.

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Appendices

Appendix 1: Aviation Terms and Abbreviations

5X: United Parcel Service
AA: American Airlines
CO: Continental Airlines
DL: Delta Airlines
FL: Airtran Airways
FX: Federal Express
UA: United Airlines
US: US Airways

ABQ: Albuquerque Sunport
ATL: Atlanta Hartsfield
AUS: Austin-Bergstrom
BDL: Hartford Bradley
BNA: Nashville
BOS: Boston Logan
BUF: Buffalo Niagara
CLT: Charlotte Douglas
CMH: Port Columbus
DEN: Denver
DFW: Dallas/Fort Worth
DTW: Detroit Metro Wayne County
EGE: Vail Eagle County
ELP: El Paso
EWR: Newark Liberty
FLL: Fort Lauderdale-Hollywood
HNL: Honolulu
IAD: Washington Dulles
IAH: Houston George Bush
IND: Indianapolis
JAX: Jacksonville
JFK: New York John F. Kennedy
KOA: Kona at Keahole
LAX: Los Angeles
LIH: Lihue
MCI: Kansas City
MFE: McAllen-Miller
MIA: Miami
MKE: Milwaukee County General Mitchell
MSN: Madison Dane County
MSP: Minneapolis-Saint Paul
MSY: Louis Armstrong New Orleans
OAK: Oakland
OGG: Kahului
OKC: Oklahoma City Will Rogers World
OMA: Omaha Eppley Airfield
ONT: LA/ Ontario
ORD: Chicago O'Hare
ORF: Norfolk
PBI: Palm Beach
PHL: Philadelphia
PHX: Phoenix Sky Harbor
PIT: Pittsburgh
PSP: Palm Sprtings
PVD: Provodence Theodore Francis Green State
RDU: Raleigh-Durahm
RIC: Richmond
RNO: Reno-Tahoe
RSW: Southwest Florida
SAT: San Antonio
SFO: San Francisco
SJC: Norman Y. Mineta San José
SJU: San Juan Luis Muñoz Marín
SLC: Salt Lake City
SMF: Sacramento
SNA: John Wayne Orange County
SRQ: Sarasota Brandenton
STL: Lambert-St. Louis
STT: St. Thomas Cyril K. King
TUL: Tulsa
TUS: Tuscon

Banked hub: A hub in which flights arrive and depart in waves.
Rolling hub: A hub in which flights arrive and depart on a regular basis throughout the day

Legacy 737: 737-100, 737-200
Classic 737: 737-300, 737-400, 737-500
Next-Generation 737: 737-600, 737-700, 737-800, 737-900

Legacy carriers: Airlines that flew interstate and international routes before airline deregulation in the US. American Airlines, Continental Airlines, Delta Airlines, United Airlines, US Airways

Narrow body aircraft: Aircraft with one aisle in these analyses
Wide body aircraft: aircraft with two or more aisles in these analyses

Appendix 2: Sample Calculations

Fuel

Airline	Aircraft	Total Gal. Fuel	Available Seat Mi.	Available Ton Mi.	Aircraft Hrs. Ramp 2 Ramp
5X	757-200	20432082	0	267532126	18532
	767-300/ -300ER	37595817	0	653702688	24194
	A300B/ C/ F/ -100/-200	27189429	0	357018540	18189
	MD-11	49181736	0	846938517	20604
	747-400	29868937	0	558975442	9501

Aircraft	Seat Mi./Gal.	Ton Mi./Gal.	Gal./Hr.
757-200	0	13.09372809	1102.529786
767-300/ -300ER	0	17.38764416	1553.931429
A300B/ C/ F/ -100/-200	0	13.13078476	1494.828138
MD-11	0	17.22059012	2386.999418
747-400	0	18.71427303	3143.767709
Airline Averages	0	15.90940403	1936.411296

	Seat Mi./Gal.	Ton Mi./Gal.	Gal./Hr.
Narrow Body Average	0	13.09372809	1102.529786
Wide Body Average	0	16.61332302	2144.881673

Emissions

Airline	Aircraft	Departures	CO_2	HC	NO_X	CO	SO_2
UA	757-200	26148	4320	0.22	23.43	8.08	1.37
	A320-100/ -200	33848	2440	0.57	9.01	6.19	0.77
	A319	19982	2310	0.59	8.73	6.35	0.73
	767-300/ -300ER	6289	5610	1.19	28.19	14.47	1.77
	777-200/ -200LR/ -233LR	7137	8100	0.66	52.81	12.76	2.56
	747-400	1577	10240	2.25	42.88	26.72	3.24

Aircraft	Total CO_2	Total HC	Total NO_X	Total CO	Total SO_2	Seats
757-200	112959360	5752.56	612647.64	211275.84	35822.76	4610464
A320-100/ -200	82589120	19293.36	304970.48	209519.12	26062.96	4785726
A319	46158420	11789.38	174442.86	126885.7	14586.86	2397720
767-300/ -300ER	35281290	7483.91	177286.91	91001.83	11131.53	1335656
777-200/ -200LR/ -233LR	57809700	4710.42	376904.97	91068.12	18270.72	1949587
747-400	16148480	3548.25	67621.76	42137.44	5109.48	587419
Narrow Body Total	241706900	36835.3	1092060.98	547680.66	76472.58	11793910
Wide Body Total	109239470	15742.58	621813.64	224207.39	34511.73	3872662

Delays

Airline

CO

Airport	Pax	% of traffic	HHI Hub?	Average Delay Min.
IAH	2768594	32.09157025	Yes	9.08509383
EWR	2133529	24.73034897		13.5624586
CLE	337990	3.917739411		
MCO	246556	2.85790159		
LAX	228720	2.651159378		
LAS	221168	2.563621971		
FLL	184604	2.139798119		
SFO	142350	1.650019838		
TPA	137215	1.590498575		
MSY	127605	1.479106298		
PHX	126219	1.463040773		
DEN	117011	1.356308193		
SEA	113583	1.316573258		
MIA	108965	1.263044691		
SAN	107466	1.24566935		
PBI	103651	1.201448586		
RSW	98678	1.143805112		
BOS	98338	1.139864074		
ORD	92496	1.072147769		
SJU	92107	1.067638758		
SAT	89743	1.040236954		
DFW	84666	0.981387985		
AUS	84152	0.975430063		2.393629124
LGA	75294	0.872754434		
HNL	73620	0.853350618		2.985645933
SNA	64221	0.744404103		4.634028892
DCA	59746	0.692533089		
PDX	51937	0.602016722		
PHL	48751	0.565086878		
BWI	39689	0.460046627		
SMF	35899	0.416115646		3.333333333
ONT	30215	0.350230765		-4.373271889
ATL	26969	0.312605444		
SJC	25977	0.301106887		1.330143541
MFE	24815	0.28763781		-1.951417004
SLC	24017	0.278387962		

Airports with no value in the delay field did not qualify for the analysis see, above methods for details.

Noise

Airline

FL

Airport	Aircraft	Departures	EPNdB	Departures X EPNdB	EPNdB/Total Departures
ATL	717-200	16316	173.7	2834089.2	
	737-700	16405	182.2	2988991	
	total depart	32721	total dB	5823080.2	177.9615599
ROC	717-200	180	173.7	31266	
	total depart	180	total dB	31266	173.7