Spring 5-16-2014

Aircraft Greenhouse Gas Emissions during the Landing and Takeoff Cycle at Bay Area Airports

Travis M. Norton
University of San Francisco, travis76435@hotmail.com

Recommended Citation

Norton, Travis M., "Aircraft Greenhouse Gas Emissions during the Landing and Takeoff Cycle at Bay Area Airports" (2014). *Master's Projects and Capstones*. 15.
https://repository.usfca.edu/capstone/15

Aircraft Greenhouse Gas Emissions during the Landing and Takeoff Cycle at Bay Area Airports

Travis Norton | MSEM University of San Francisco | Spring 2014

Contents

Introduction

The aviation industry is a large global industry and has a significant impact on the environment. During all phases of air travel, many types of pollutant emissions are released. It is because of this that air travel is an anthropogenic contributor to global climate change. The pollutants' emitted from jet engines include both criteria air pollutants, defined by the Clean Air Act (CAA) as common pollutants considered harmful to public health and the environment, and greenhouse gases (GHG) (EPA 2012). Both types of pollutants have been known to have serious health effects and a significant impact on the environment. The industry is consistently growing, so the impact these emissions have are of increasing concern. It is unknown how much exact impact the industry has on the environment and people's health, but ongoing efforts to model and predict the aviation industry's exact impact are under way. Difficulties in monitoring and correctly modeling aircraft emissions hinder many viable mitigation efforts. However, new strategies are being developed to reduce the impact that the growing market has around the world.

Aviation Industry

The aviation industry is one of the largest markets in the world. Roughly 2.2 billion passengers are moved annually by air transport and the industry globally employs 32 million people (Gil et al. 2013). It is estimated that the industry has an economic impact of 3,6 billion USD. This represents almost 7.5% of the world domestic product. Figure 1 shows the international and domestic growth in air travel markets in revenue passenger kilometers (RPK) from 2007 to 2012. RPK measures traffic for airline flights by multiplying the distance the flight traveled by how many revenue-paying passengers were aboard the flight. It is a standard unit of measure in the transportation industry. Figure 1 was obtained from the International Air Transport Association (IATA) December 2012 Air Transport Market Analysis. The figures indicate a steady growth in international and domestic travel and the industry in general (IATA 2013). Specifically there is a dip in the market during 2008 which corresponds with the onset of the economic recession in the United States. The figures on the right show air travel market growth by region for the months of November 2012 and December 2012. The graphs indicate little variation in growth between each month and show an overall growth in the industry worldwide with the exception of India's domestic travel.

With such a strong global presence, it becomes increasingly important to evaluate the environmental effects of air transport. The aviation industry is

Figure 1 – Total domestic and international air travel market growth measured in revenue passenger kilometers (RPK) from 2007-2012 (IATA 2013).

responsible for 2% of total anthropogenic CO2 emissions and estimated to increase to 3% by 2050 (IPCC TAR 2001).

Air travel is the most energy intensive form of transport (Gossling et al. 2007). Figure 2 brakes down the European travel by mode of transport in 2000 with regard to number of trips, distance traveled and percent GHG emitted, and also makes projections for 2020 (Peeters et al. 2005). Air transit clearly makes up the majority of tourism mode of travel GHG emissions. As the largest GHG emitter in the European modal split, the importance of mitigation research becomes clear.

Greenhouse Gases

In addition to the emissions produced from ground activities at airports, aircrafts produce a considerable amount of pollutant emissions into the atmosphere. GHG emissions from jet fuel combustion are estimated to increase between 200 and 500% from 1995 values by 2050 (Olsthoorn 2001).

Typical aircraft jet emissions are shown in the flow chart in figure 3 (Weubbles 2007). These include GHG such as carbon dioxide (CO_2), water vapor,

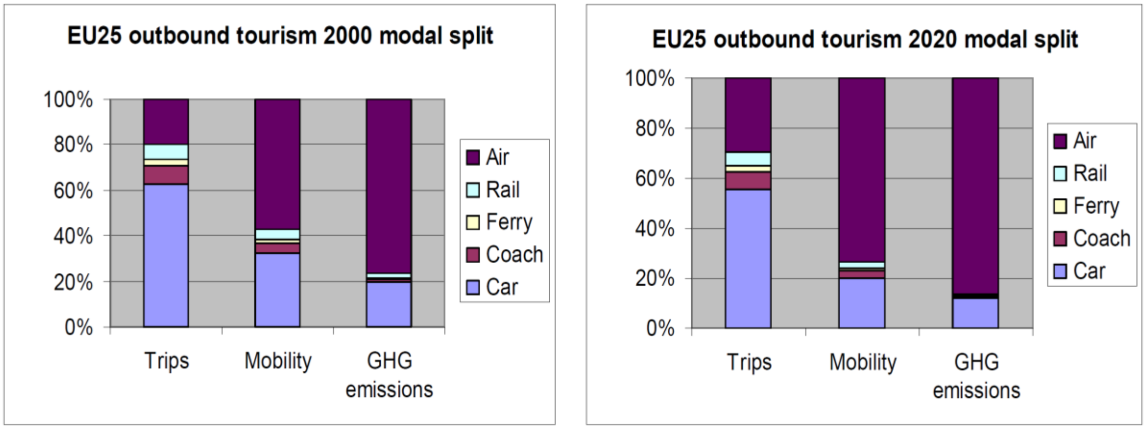


Figure 2 – European modal split of total trips, mobility measure in distance actually traveled and GHG emissions for outbound tourism in 2000 and projected in 2020 (Peeters et al. 2005).

ozone (O_3), nitrous oxide (N_2O) and methane (CH_4) in addition to other radiative forcing sources such as sulfur oxides (SO_x) and soot.

CO_2 emissions are the most understood and well-studied pollutant from jet engine emissions. Table 1 indicates that CO_2 makes up the majority of the environmental impact from aircraft jet engines. (Macintosh et al. 2009). CO_2 had a radiative forcing value of 25 mW/m², while the total radiative forcing impact from aircraft emissions was 48mW/m². Radiative forcing is defined by the IPCC as the change in irradiance at the tropopause after allowing the atmospheric temperatures to return to radiative equilibrium (IPCC 2007). The impact of this is further explained in the Environmental Impact section of this report. Figure 4 shows the same trend is true when looking at global anthropogenic GHG sources.

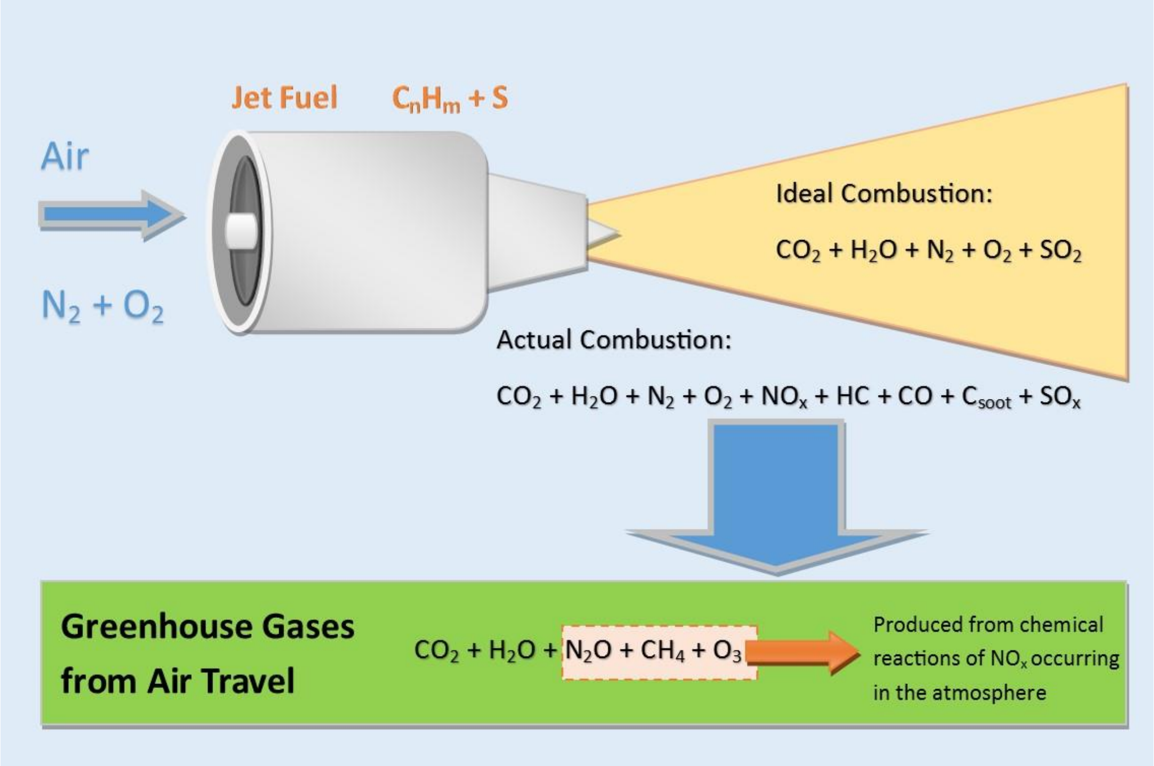


Figure 3 – This schematic shows the climatic impacts of aviation by-products (Weubbles et al. 2007).

Table 1

Radiative forcing due to aircraft emission in 2000 (Macintosh et al. 2009)

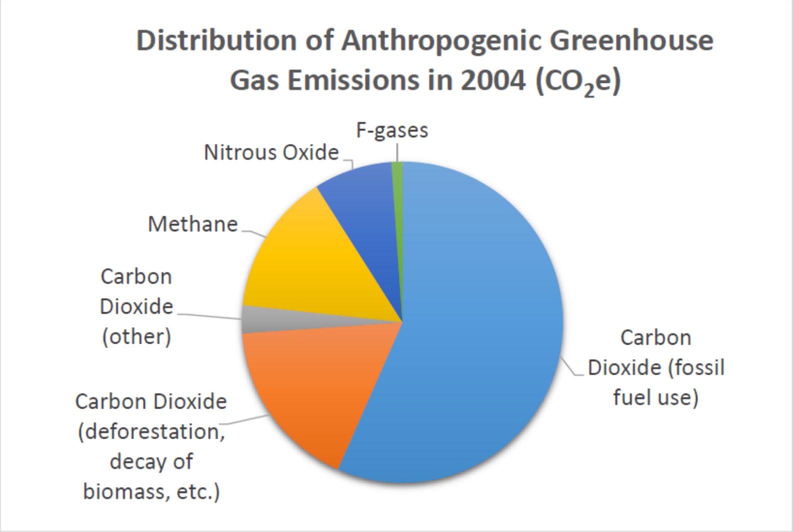
Emitted Pollutant	Radiative Forcing (mW/m2)	Level of Scientific Understanding
CO_2	25	Good
NO_x[1]		
O_3	22	Fair
CH_4	-10	Fair
H_2O	2	Fair
Contrails	10	Fair
Cirrus	30 (10-80 range)	Poor
SO_x[2]	-3.5	Fair
Soot	2.5	Fair
Total (without cirrus cloud effects)	**48**	

1. **NOx emissions O_3 in the troposhere and removes CH_4 from the atmosphere resulting in negative forcing**
2. **2. Sox emissions form sulfur aerosols which reflect heat, resulting in a negative forcing effect.**

CO_2 emissions from fossil fuel use make up the overwhelming majority of anthropogenic GHG emissions, around 57%, with roughly 13% of those GHG emissions coming from the transportation industry (IPCC 2007).

Environmental Impact

Once released from jet fuel combustion, GHGs enter the atmosphere, where they have both a direct and indirect effect. Some of these gases start out as inert, but may react with other chemicals in the environment to produce an entirely different pollutant. The environmental impact of these newly released pollutants may be in the form of radiative forcing, ozone depletion, or some other impact on the global climate. For example, pollutants like CO_2 have a direct warming effect on the atmosphere. Meanwhile, NO_x will oxidize in the atmosphere with CH_4, removing the high global warming potential pollutant from the atmosphere, resulting in a cooling effect. However, it will also react in the troposphere and form O_3. The net reactions from the NO_x reactions are still positive due to the large impact that O_3 has on the environment.



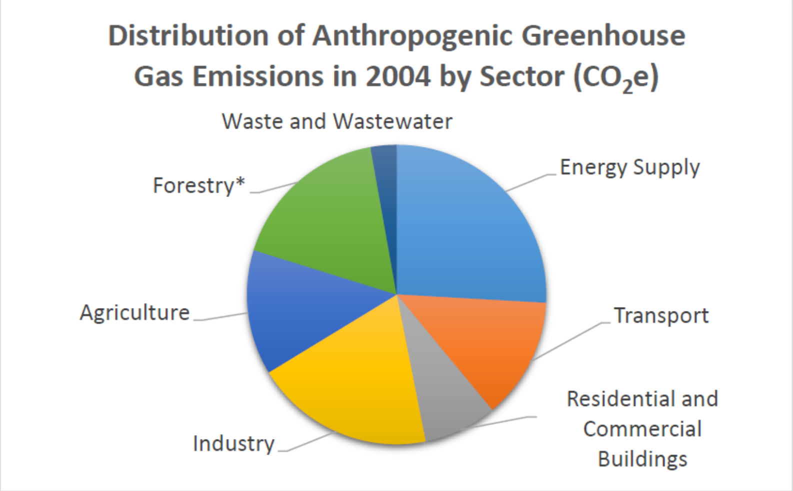


Figure 4 – Global anthropogenic GHG sources in 2004 (IPCC 2007).

Planes only fly in the troposphere, but the effect of these jet engine emissions transcend into the stratosphere. The ultimate environmental impact of these released pollutants will vary. Table 1 summarizes these pollutants and quantifies their impact by calculating the amounts of radiative forcing from global aircraft emissions in 2000. Radiative forcing is the change in net energy of the earth and its atmosphere associated with an external factor. It can be calculated from the entering shortwave radiation to the atmosphere minus the exiting shortwave and longwave radiation. In the case of GHGs, radiative forcing refers to the shortwave radiation entering Earth's atmosphere and getting absorbed by the GHG. It also occurs when outgoing

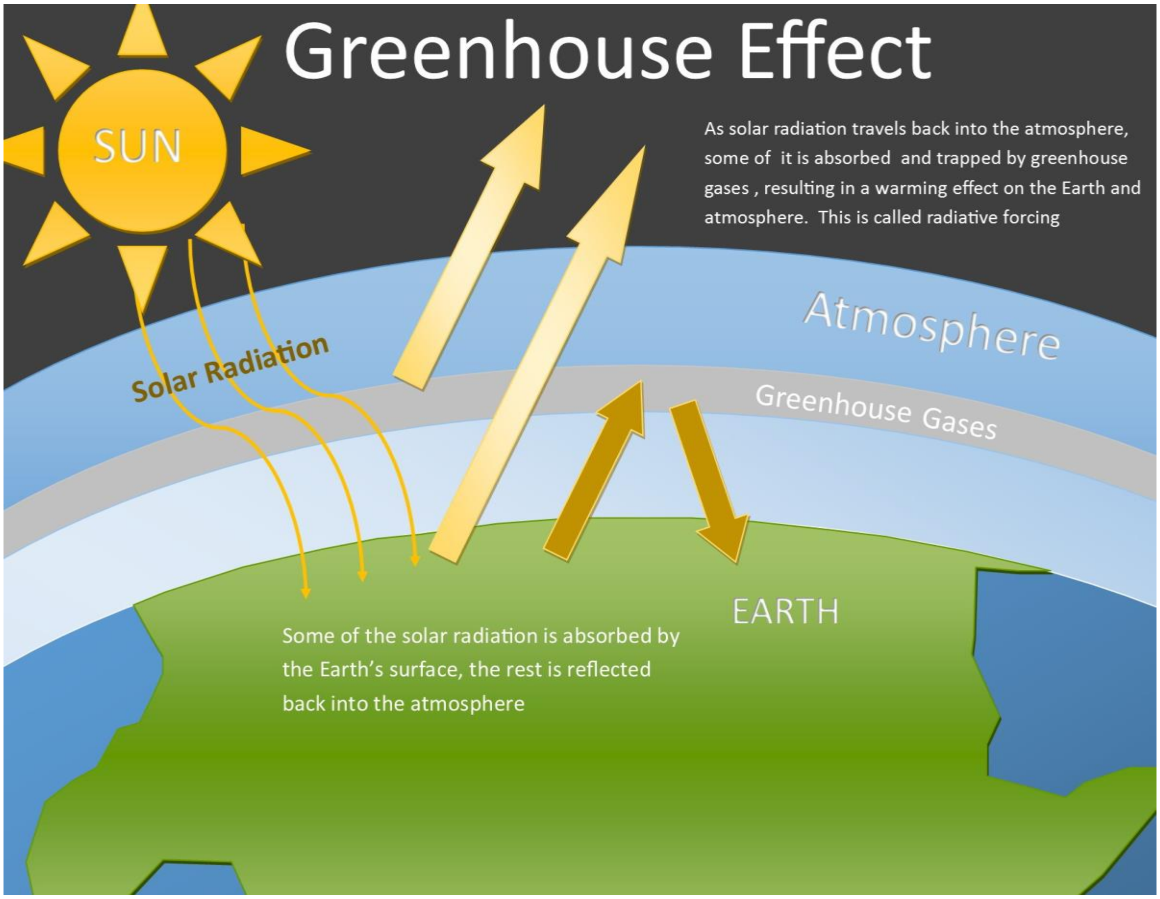


Figure 5 – A schematic of the greenhouse effect. Solar radiation enters the Earth's atmosphere, is absorbed by the Earth and the remainder gets reflected back into the atmosphere. While most radiation exits the atmosphere, some is trapped by greenhouse gases. This is called radiative forcing.

longwave radiation gets reflected off of the Earth's surface and gets absorbed by GHG before exiting the atmosphere. Figure 5 shows a schematic of this effect.

As also indicated in Table 1, much of the scientific understanding on the exact environmental effect of these pollutants ranges from fair to poor, with CO_2 as an exception. The estimates made in Table 1 are based on modeling predictions and knowledge of atmospheric chemistry. They should be used as a relative reference on each pollutants environmental impact.

Regulatory Compliance

Airports across the United States are required to meet air quality standards that are set in accordance with their State's implementation plan (SIP) to meet the national ambient air quality standards (NAAQS) on criteria pollutants (FAA 1997). Most of the specific air quality requirements set for airports are defined in the General Conformity Regulation (FAA 1997). Emissions and ambient air quality monitoring are not required by the general conformity regulations, but may be required at the request of local agencies. For the purposes of developing the SIP in

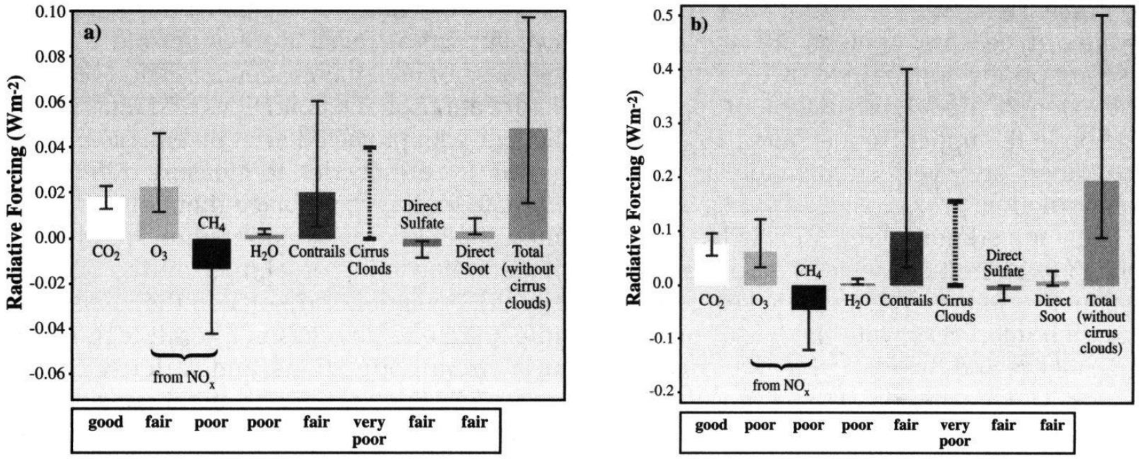


Figure 6 – Global and annually averaged estimates of radiative forcing for subsonic aircraft fleet for (a) 1992 and estimates for (b) 2050. Also indicated is the level of scientific understanding in relation to climatic response. (Weubbles 2007).

each state, airports will use dispersion modeling to project emissions inventories. Dispersion modeling uses mathematical formulas to describe the dispersion of a pollutant from a particular source in the atmosphere. It can predict concentrations downwind, as well as determine compliance with NAAQS or other regulatory requirements. The FAA's Emissions and Dispersion Modeling System (EDMS) is used to produce these emissions inventories and assess the air quality impacts from aviation sources, including aircraft (KB 2013).

National regulations do not apply to aircraft GHG emissions, with the exception of those that are also regulated by the Clean Air Act, such as nitrogen oxides and ozone. Currently, GHG emissions inventories are not mandated by national or state agencies; however, a large percentage of aircraft emissions are GHG. Figure 6 shows the distribution of aircraft GHG emissions and their overall radiative forcing effect measured in 1992 and estimates for 2050 (Weubbles 2007). As indicated, the science behind contrails is not well understood, and as such, there are few mitigation options for them. In the figure, chart "a" shows that CO_2 is second to only contrails as the biggest climatic effect in terms of radiative forcing. This is true only when considering the overall net impact of O_3 and CH_4, since both are from NO_x emissions. This trend is expected to continue as when looking at 2050 predictions made in chart "b." The total radiative forcing contribution from aircraft GHG emissions is expected to be roughly five times what they were in 1992. Because of the impact of GHG have on climate, it is important analyze the exact impact that an airport's operations have on GHG emissions and what can be done to mitigate those emissions.

Landing and Takeoff Cycle

Flight operations that occur on the local level are called the landing and takeoff cycle (LTO). The cycle begins once an aircraft reaches the mixing zone (3,000 ft) upon its descent. The cycle continues as the aircraft lands, taxis to the gate, taxis back out for takeoff, and climbs out past the mixing zone during takeoff

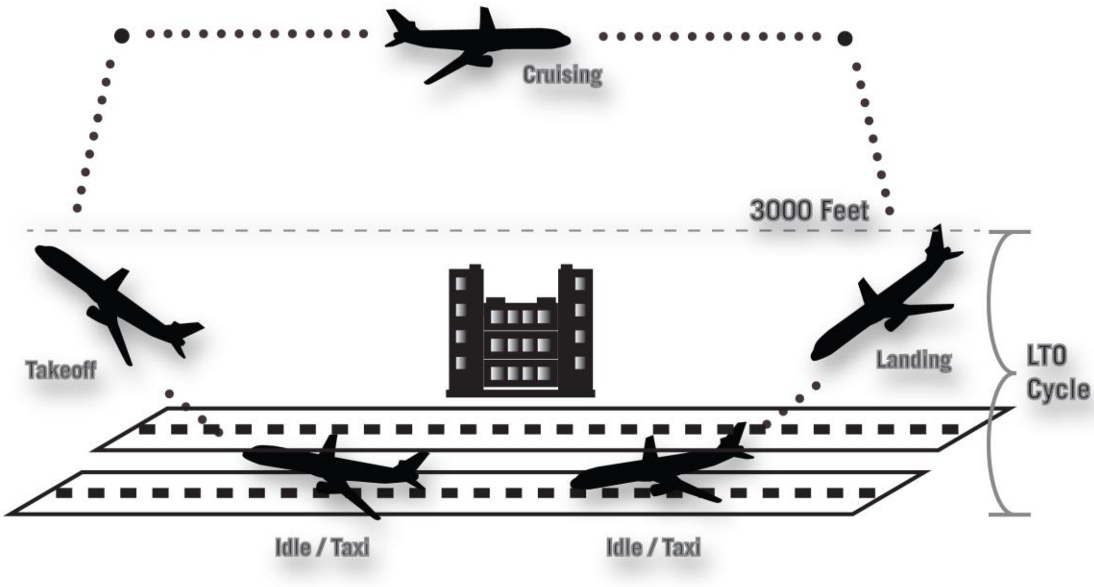


Figure 7 – Schematic of the LTO cycle, including landing, idle/taxi and takeoff. All operations occurring below 3,000 ft are included. Cruising occurring above 3,000 ft is not included in the LTO cycle.

(Kim 2009). This is shown in figure 7. The FAA's Emissions Dispersion Modeling System (EDMS) is used to model an aircraft's fuel consumption and emissions during the LTO cycle.

Roughly ten percent of all types of aircraft emissions, except hydrocarbons and carbon monoxide, are produced during ground-level and LTO operations. For carbon monoxide and hydrocarbons, LTO operations make up thirty percent of emissions (FAA 2005). LTO operations have a significant contribution to an airport's GHG emission inventory, despite representing only ten percent of an aircraft's total emissions. The LTO cycle aircraft emissions can represent up to 70% of an airport's emissions inventory (MAC 2010). Aircraft cruising emissions are not typically included in an airports emissions inventory, as the emissions do not affect the local environment (Kim 2009). Operational strategies can be used to mitigate these emissions at individual airports. The strategies used to mitigate emissions in the LTO cycle will have a direct impact on emissions in the cruising phase as well.

Bay Area Airports

Table 2 - Total Arrival and Departure Operations

	2011	2012	2013
SFO	400,805	419,867	418,719
OAK	150,651	152,125	144,143
SJC	124,731	122,025	126,848

The San Francisco Bay Area is the third largest aviation market in the United States. The largest airports in the area include San Francisco International Airport (SFO), Oakland International Airport (OAK) and Norman Y. Mineta San Jose International Airport (SJC). The FAA categorizes airports based on their activities, the main distinction being the percentage of the total US annual passenger boardings (FAA 2012). Based on this, SFO is defined as a Large Hub, representing >1% of annual passenger boardings, and OAK and SJC are defined as Medium Hubs, representing 0.25-1% of annual passenger boardings (FAA 2012). Figure 8 is a map of the Bay Area and shows each airport's relative location. Table 2 shows the total number of arrival and departure operations for all three airports from 2011 through 2013. San Francisco International Airport has over twice as many total flight operations than either of the other two.

SFO

San Francisco International Airport (SFO) serves over 41 million passengers annually including both domestic and international travel. This includes nonstop service to over 75 domestic airports and 30 internationally (San Francisco International Airport 2012). In fiscal year (FY) 2012, SFO had 417,430 takeoffs and landings of 56 airlines in addition to shipping 385,113 metric tons of cargo (SFO 2012). It is defined by the FAA as a Large Hub.

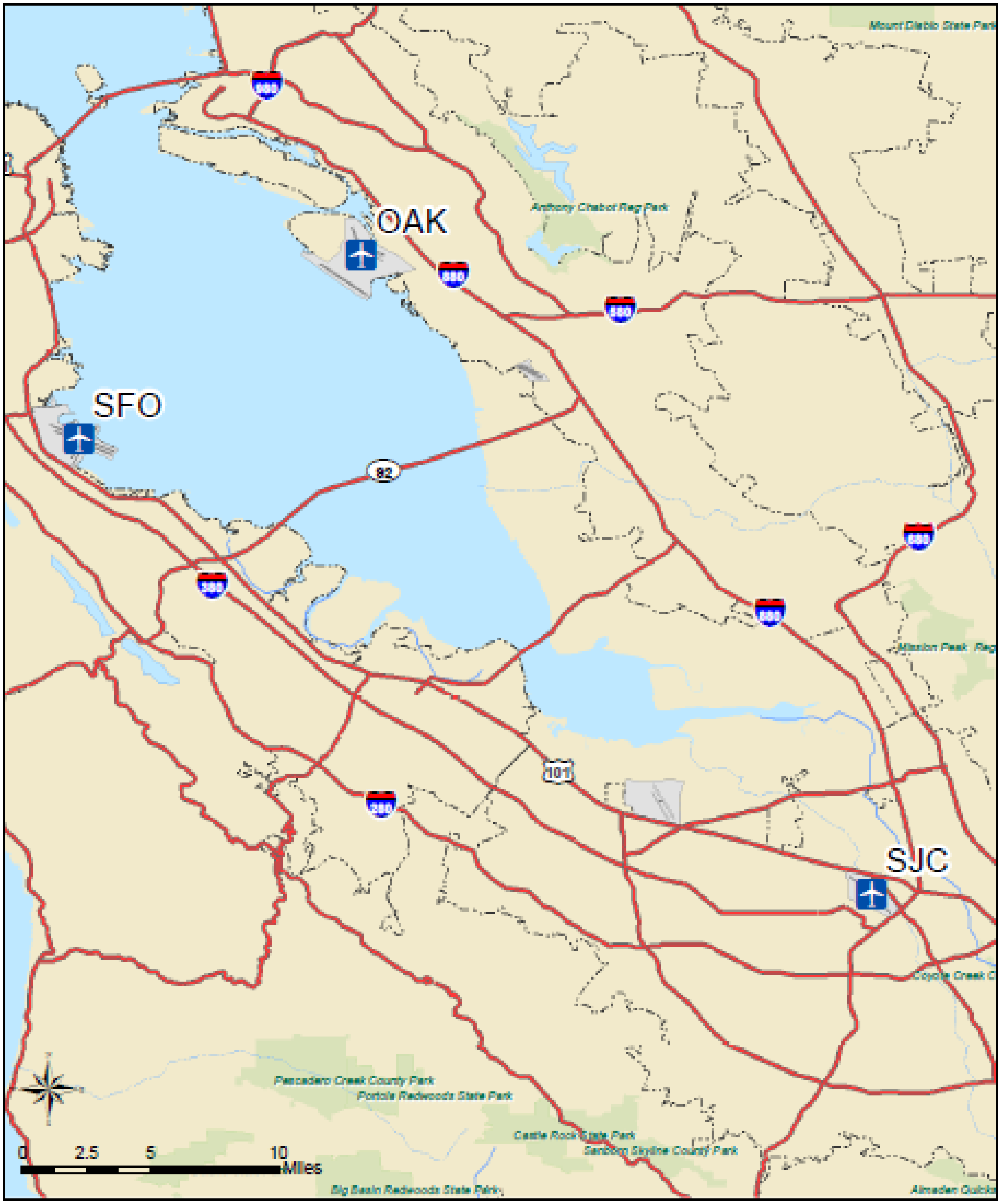


Figure 8 – ArcMap of the San Francisco Bay Area, including San Francisco International (SFO), Oakland International (OAK) and Norman Y. Mineta San Jose International (SJC) airports (ESRI 2008).

In 2010 SFO started installing preconditioned air to several boarding areas, thereby reducing the need of Auxiliary Power Units (APUs) while boarding and deplaning passengers. By eliminating the need for the aircrafts to run idle during this process, less jet fuel is burned, thereby reducing the GHG emissions. In an effort to offset GHG emissions from airport operations by carbon sequestration, SFO has planted 2,020 trees of different varieties around the airport in recent years. The airport has also been developing a Climate Action Plan (CAP) outlining its GHG reduction activities since 2008. This is in compliance with San Francisco law that mandates all city departments to develop a CAP that outlines procedures for meeting GHG reduction goals.

SFO does not have mandatory programs for requiring emission reductions or fuel efficiency of aircraft, but it does encourage environmentally beneficial operational procedures. One such example is the airport's support of single-engine use during aircraft taxiing to reduce fuel consumption and resulting GHG emissions (SFO 2011). In 2008 the City and County of San Francisco signed into law Ordinance No. 81-08, Climate Change Goals and Action Plan. This mandated GHG reductions of 25% below 1990 levels by 2017 and 40% by 2025. This mandate, however, only extends to SFO-controlled operations, not including airline controlled aircraft operations. SFO has stated that it plans to refine and supplement emissions estimates from these aircraft operations in the future (SFO 2012).

OAK

Oakland International Airport (OAK) transports over 10 million passengers annually with both domestic and international travel (Oakland Airport 2014). In addition, it transports over a billion pounds of cargo annually. It is defined by the FAA as a medium hub.

As part of an environmental management decision to improve air quality, OAK has installed ground power at all terminal gates. OAK also has installed preconditioned air units in several gates throughout the airport, which will reduce GHG emissions by eliminating the need for aircraft to burn jet fuel in order to supply power and preconditioned air while boarding and deplaning (OAK 2014). The installation will also be done at the remaining gates during upcoming renovations.

The City of Oakland established an Energy and Climate Action Plan in December of 2012 to address GHG emissions and relevant reduction strategies in order to meet regulatory emission goals; however, airport GHG emissions were not a component of this plan (City of Oakland 2012).

SJC

Norman Y. Mineta San Jose International Airport (SJC) is located in the heart of Silicon Valley and transports over 8 million passengers annually (Mineta San Jose International Airport 2014). In addition it transports over 94 million pounds of cargo annually. It is defined by the FAA as a medium hub.

In an ongoing effort started in 1998, all airlines at SJC are encouraged to perform single or reduced-engine taxiing in a safe and efficient manner. In 2001 SJC constructed a second air carrier runway and extended runway 12L/30R from 4,400' to 11,000'. The new and extended runway will reduce congestion and, therefore, aircraft delays that may result in increased GHG emissions.

SJC was awarded the FAA's Voluntary Airport Low Emissions (VALE) grant in 2009. The airport was the first in the western United States to receive the award. The $4.6 million grant was used in coordination with the airport's modernization program to provide all aircraft gates with pre-conditioned air (PCA) and ground power. This allows the airport to use less jet fuel while parked at the gate (City of San Jose 2014).

STUDY GOALS

A method developed by the Intergovernmental Panel on Climate Change (IPCC) was used to produce an emissions inventory for Bay Area airports (IPCC 2001). FAA data was used along with existing models to characterize the LTO GHG emissions at SFO, OAK, and SJC. A comparative analysis was done to relate the Bay Area airport LTO GHG emissions to other airports both domestically and globally. Mitigation strategies were then suggested to reduce LTO GHG emissions at these airports. Current strategies at the Bay Area airports were then analyzed to suggest what new areas should be focused on.

Methods

This study is a modeling analysis to produce a comparative evaluation of Bay Area airports and suggest operational best practices to reduce LTO GHG aircraft emissions. The purpose of the study is to find out how each of the three Bay Area airports compare to similar airports with regard to GHG emissions caused by LTO-based fuel consumption. A list of operational best practices for mitigation of these emissions is made and specific recommendations are made for each airport. A similar method of analysis to that used in Song 2012 for Korean airports is used here for Bay Area airports.

To start this study, operational information for each airport was obtained from FAA databases. The data was analyzed within the time frame of January 2011 to December 2013. As a control measure, all the data were collected from the same time frame and from three different years to average out any years that may have been outliers. The specific information that was gathered comes from FAA Operations and Performance Data Traffic Flow Management Counts (TFMSC). This database provides the traffic counts by airport for different data groupings. The data groupings used in this study are by airport location, aircraft type and by year. Departure and arrival counts are collected for each year and broken down by aircraft type. The aircraft types representing 90% of the airports' total operations for the year were sorted, and then traffic count data was collected and input into the EDMS modeling software. This data is found in the Appendix Tables 1-3.

Within EDMS nine emissions inventories were made, one for each year and at each airport. The method used is the same one presented in the IPCC Good Practice and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2001). All aircraft types were added to the emissions inventory along with each aircraft type's corresponding operational information. EDMS uses engine specifications to calculate emissions for each aircraft type, then compiles the whole inventory for the year. EDMS produces fuel consumption, water vapor, and CO_2 inventories for the LTO phase. An evaluation of the environmental impact of ground service equipment and other airport generated GHG has not been done. The actual effect that aircraft produced water vapor has on the environment is still not well known, but speculated to have a large impact (Macintosh 2009). The basis for this is a result of water vapor's effect on cloud or contrail cirrus formation, which have a large radiative forcing effect. However, this process happens at altitudes higher than 3,000 ft, and not in the LTO phase. It is also concluded that the water vapor released from jet engine emissions will not have a significant impact on the global water cycle. Therefore, the water vapor emissions are reported but not calculated in total CO_2 equivalence (CO_2e). The fuel consumption data is used to calculate the GHG emissions using Method 2 as described in the Airport Cooperative Research Program (ACRP) Report 11 (Kim 2009). Using a simple model, methane and nitrous oxide emissions are calculated as follows:

$$\text{Jet fuel} = 0.27\text{g } CH_4/\text{gal fuel}$$

$$\text{Jet fuel} = 0.21\text{g } N_2O/\text{gal fuel}$$

Jet A fuel is assumed as the fuel used and no analysis was done with Aviation gasoline (Avgas). While the two fuels produce different emission profiles, most modern commercial airliners use jet fuel and not Avgas (Maurice 2001). The resulting CO_2e from CH_4 and N_2O are calculated using the global warming potential (GWP) data from table 2.14 of the IPCC Fourth Assessment Report, using the 100 year time horizon (Table 3) (IPCC 2007).

Table 3

IPCC Fourth Assessment Report CO_2e	GWP (100 year time horizon)
CO_2	1
CH_4*	25
N_2O	298

* The GWP for CH_4 includes indirect effects from enhancements of O_3 and stratospheric water vapor (IPCC 2007)

The aircraft GHG emissions inventories are then be compared to similar airports to compare their relative efficiency. The airports were selected based on airport size. As a large hub, SFO was compared with other large hubs, including Los Angeles International Airport (LAX), John F. Kennedy International Airport (JFK), Newark Liberty International Airport (EWR), LaGuardia Airport (LGA), and Minneapolis-St. Paul International Airport (MSP). Because of the lack of data available for medium and small hubs domestically, OAK and SJC were compared to similar sized major international airports in Korea. These include Gimpo (RKSS), Jeju (RKPC), and Gimhae (RKPK). SFO and Incheon International Airport (RKSI) were also included in this comparison to provide a larger hub benchmark comparison.

The interactive research tool AirportGEAR was then used to produce a list of recommended operational strategies for GHG mitigation. The ACRP is a program controlled by the Transportation Research Board (TRB), which is funded by the FAA. AirportGEAR was developed by the ACRP and is designed to assist airport operators analyze technical information and choose various GHG reduction strategies (CDM 2012). It is further defined in ACRP Report 56. Out of the program's 125 different operational strategies, 30 are specifically related to reducing GHG emissions produced by aircraft during the LTO cycle. The most effective strategies are presented to provide practical solutions to GHG assessment and reduction. Using these strategies, specific recommendations will be made for each airport. AirportGEAR was developed in 2012, and due to its recent development, many airport operators have not yet utilized it to prioritize and evaluate different GHG mitigation strategies.

Results and Discussion

The TFMSC database produced operational reports for SFO, OAK and SJC grouped by aircraft equipment and by year. The aircraft equipment representing 90% of the total operations were used to produce the tables 1-3 in the Appendix. SFO has the largest number of flights and the smallest number of aircraft type represented with 20 different aircraft types totaling 1,125,804 aircraft operations including both landing and takeoff. This is followed by OAK which has 39 different types of aircraft equipment totaling 404,133 aircraft operations. SJC has 34 different types of aircraft equipment and a total of 339,064 landing and takeoff operations.

This arrival and departure information was imputed into the FAA's EDMS software to produce emissions inventories for the three airports from 2011 through 2013. This provided fuel consumption, CO_2, and water vapor data. The fuel consumption data was used to calculate the resulting CH_4 and N_2O inventories. Their CO_2e values were then calculated from the GWP in table 3. As stated earlier, water vapor is not included in the CO_2e analysis. Table 4 shows this information and the total CO_2e for each airport reported in metric tons per year. SFO had an average CO_2e emissions of 506,409 metric tons per year during the period of study. OAK had an average CO_2e emissions of 160,726 metric tons per year during the period of study. And SJC had an average CO_2e emissions of 106,830 metric tons per year during the same period of study.

In each reported inventory, the CO_2 produced from LTO aircraft emissions represented over 99.5% of the total GHG emissions. Despite the much larger GWP of CH_4 and N_2O, they represent only a small portion of the anthropogenic GHG produced during the LTO cycle, meaning additional efforts for mitigation should be primarily focused on CO_2 specifically.

Table 4
Aircraft Greenhouse Gas Emissions Inventories (Metric Tons / Year)

	SFO			OAK			SJC		
	2011	**2012**	**2013**	**2011**	**2012**	**2013**	**2011**	**2012**	**2013**
Fuel Consumption	156,338	161,815	161,440	50,149	51,721	50,346	33,777	33,060	34,336
Carbon Dioxide	493,248	510,526	509,344	158,219	163,178	158,841	106,566	104,304	108,332
Water Vapor	193,391	200,165	199,701	62,034	63,978	62,278	41,782	40,895	42,474
Methane	14	14	14	4	5	4	3	3	3
Methane (CO_2e)	340	352	351	109	113	110	73	72	75
Nitrous Oxide	6	6	6	2	2	2	1	1	1
Nitrous Oxide (CO_2e)	1,652	1,710	1,706	530	546	532	357	349	363
Total CO_2e	495,239	512,588	511,400	158,858	163,837	159,482	106,996	104,725	108,769

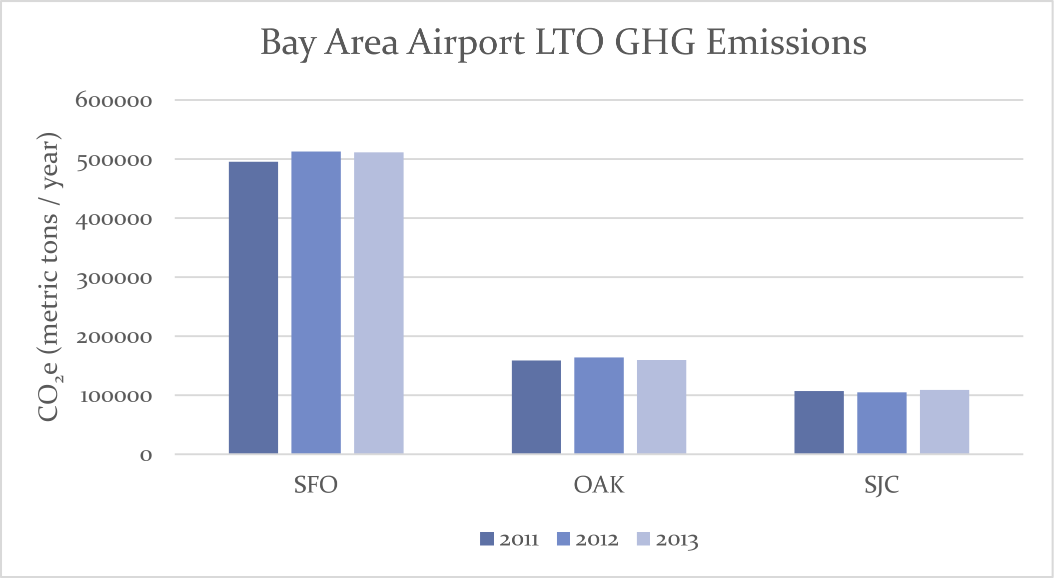


Figure 9 – Bay Area airport LTO GHG emissions for the years 2011-2012 is shown.

For SFO and OAK, 2013 saw a slight decrease in total operations and therefore total CO_2e emissions, whereas SJC had slight increases every year. This falls in line with SJC's projected growth and recent airport expansions (Mineta San Jose International Airport 2014). Figure 9 shows the scope of the Large Hub (SFO) emissions compared to the other two Bay Area airports. Figure 9 also shows off how minimal the relative changes are from year to year.

Additional airports were studied to compare bay area airports to airports of similar size. All airports studied completed a similar GHG emissions inventory to the one conducted in this study (see references in Table 5 caption), using the guidelines presented in the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2001). Table 5 compares SFO to other airports meeting the Large Hub distinction. The US Department of Transportation's passenger boarding statistics was used to identify comparable airports (USDOT 2012).

Table 5 shows GHG emissions inventories from the following airports: SFO, Los Angeles International Airport (LAX), John F. Kennedy International Airport

(JFK), Newark Liberty International Airport (EWR), LaGuardia Airport (LGA), and Minneapolis-St. Paul International Airport (MSP). All six these of these airports are classified by the FAA as Large Hubs. Included in Table 5 are the airports LTO cycles for the given year and their inventoried LTO cycle aircraft GHG emissions listed in metric tons CO_2e. LTO cycle data was calculated using operational data from TMFSC in the FAA database. This was done by dividing in half the total arrivals and departures.

Table 5

Large Hub Total and Boeing 777-200/300 LTO Cycles

Airport	LTO Cycles[1]	Boeing 777-200/300 LTOs	GHG Emissions (CO2e)
LAX	275,771	5,030	634,424[a]
JFK	223,144	7,833	866,027[b]
EWR	218,180	5,335	588,366[c]
MSP	217,076	5	327,736[d]
SFO	200,403	4,219	495,239[c]
LGA	191,311	0	428,742[c]

1. **Operational data based on TMFSC data from FAA databases**

[a] Based on 2009 emissions inventories (LAX 2013)

[b] Based on 2011 emissions calculations completed in this study

[c] Based on 2008 emissions inventories (Peeters 2010)

[d] Based on 2009 emissions inventories (Metropolitan Airports Commission 2010)

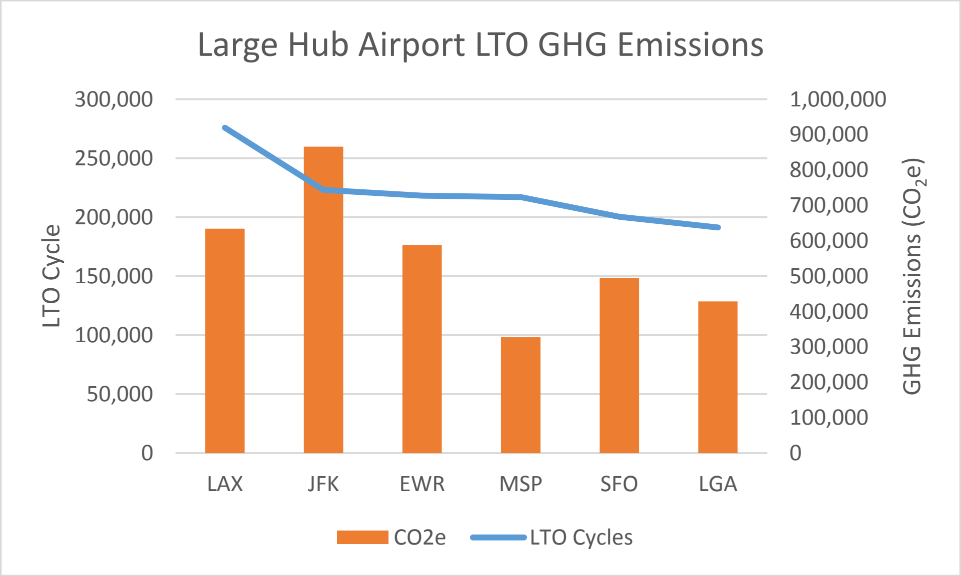


Figure 10 – GHG emissions inventories six large U.S. airport hubs are arranged by decreasing LTO cycles per year at each airport.

The data in table 5 show a predictable trend of decreasing GHG emissions with decreasing airport size with the exception of JFK and MSP. This is highlighted in Figure 10. While it is possible that there was an error in calculating this data, it is unlikely as the method described by both the New York Port Authority closely and Metropolitan Airports Commission matches the method used in this study, where operational information for individual aircraft engine types were used in EDMS. A more likely explanation for this is that since the emissions data is calculated by aircraft operations and not passenger boarding totals, that JFK had more larger-GHG-emitting aircraft land and takeoff at its airport than the others in this study proportional to its total LTO cycles. MSP likely had fewer larger-GHG-emitting aircraft land and take off at its airport than the others in this study proportional to its total LTO cycles. An example of this is evidenced in Table 5. Column 2 shows Boeing 777 LTO's at each airport.

In the Appendix to this report, there are four tables. Tables 1 through 3 show the typical aircraft types at each of the Bay Area Airports. The most commonly used aircraft type is the Boeing 737 at SJC and OAK and the Airbus A320 at SFO. These are lighter aircraft and are designed for shorter distances. The Boeing 737 has a maximum range of 3,440 nautical miles (Boeing 737 2014). The Airbus A320 has a maximum range of 3,790 nautical miles (Airbus 2014). The Appendix Table 4 shows a variety of aircraft and their typical emissions factor per LTO. The 737 and A320 engines produce 2740 and 2440 kg CO_2 /LTO respectively (Climate Registry 2014). Larger aircraft typically fly farther, carry more passengers and can produce exponentially more GHG. They can greatly add to an airport's GHG inventory. For example the Boeing 777-200 has a maximum range of 5,240 nautical miles (Boeing 777-200 2014). Its engines typically produce 8,100 kg CO_2/LTO, almost three times that of the 737 and A320 (Climate Registry 2014). Table 5 shows that JFK has much more 777 aircraft per year than the other airports and MSP has much less. This shows that the exact airport type can play a key factor in determining GHG emissions.

Because GHG emissions inventories are not mandated by federal regulations, and because the environmental impact of Medium Hub airports is less than that of much larger hubs, there are not many environmental impact studies of GHG LTO emissions inventories from comparable sized airports to SJC and OAK. Because of this, international airports were analyzed of comparable size. A study by Song of Korean airports generated GHG emissions inventories for the following airports: Incheon (RKSI), Gimpo (RKSS), Jeju (RKPC), and Gimhae (RKPK) (Song 2012).

Table 6

LTO Cycle GHG Emissions Inventories at Korean Airports

Airport Code	LTO Operations	GHG Emissions (CO$_2$e)
RKSI (Incheon)	214,853	628,000a
SFO	200,403	495,239b
RKSS (Gimpo)	118,514	199,000a
RKPC (Jeju)	103,426	152,000a
OAK	75,322	158,858b
SJC	62,362	106,996b
RKPK (Gimhae)	62,225	96,400a

a. Based on 2010 emissions inventories (Song 2012)

b. Based on 2011 emissions calculations completed in this study

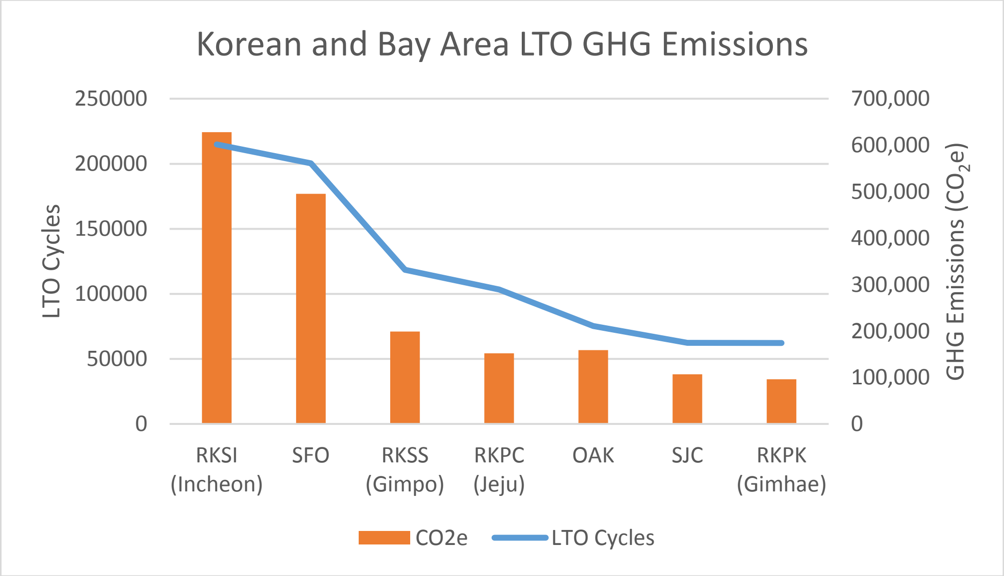


Figure 11 – GHG emissions inventories for Korean and Bay Area airports arranged by decreasing LTO cycles per year at each airport.

Table 6 shows the emissions inventories of the Korean airports as well as SFO, SJC, and OAK. Figure 11 shows that the airports follow the general trend of decreasing GHG emissions with decreasing LTO cycles. RKSS and RKPC are slightly below the trend indicated in figure 11. Given the analysis done for figure 10, one would expect the average aircraft at RKSS and RKPC to be smaller engine size and produce less GHG than that of OAK. This is because OAK has roughly the same GHG emissions inventory as RKPC, but RKPC has nearly 25% more LTO cycles. This further proves that GHG emissions can be estimated by LTO operations, but in order for an accurate GHG inventory, emissions for each aircraft type must be used.

Recommendations

AirportGEAR was used to identify the GHG mitigation strategies that specifically address aircraft emissions. Of the 125 total strategies in the program, 30 pertain to addressing aircraft GHG emissions. These strategies were prioritized by their GHG reduction potential and their effect on LTO cycle emissions, and were given a score. The top fifteen mitigation strategies are presented in table 7. Table 7 consists of a list of reduction strategies taken directly from AirportGEAR and a synopsis of its benefits.

Table 7
GHG Reduction Strategies from AirportGEAR (CDM 2012)

Reduction Strategy	Description	Pros/Cons
Create a Carbon Offset Purchasing Strategy	Works to achieve a net CO_2 emissions inventory of zero over the course of a year by purchasing carbon credits. Often done through funding of off-site projects that reduce GHG emissions.	Helps to meet GHG regulations or reduction mandates. Requires solid estimates of future GHG emissions. Cost of carbon credits depend on the market which can be highly volatile.
Develop and Apply or Sell Carbon Offsets	By generating carbon credits, airports can generate revenue from GHG reduction projects, or alternatively apply those credits towards its own GHG inventory	Promotes implementation of GHG reduction technologies and boosts the airports public image. The revenue stream created from carbon credit sales is highly variable.
Support Optimized Departure Management on Existing Runways	Improves efficiency of aircraft movement through the use of decision-making tools.	Fuel savings from optimized aircraft operations will result in a reduction of GHG emissions. Direct cost needed initially for hardware and software upgrades and training of airport personnel.
Design Airfield Layout to Reduce Aircraft Delay	Redesigning the airfield layout to improve airport traffic flow and decrease aircraft delay	Decongestion of runway traffic will result in fewer GHG emissions from idling aircraft. Some airports may have limitations on possible design changes.
Develop a Climate Action Plan (CAP)	Focuses on GHG management on the time scale of 2 - 50 years. Includes target goals, timelines and recommendations for meeting these goals	Helps airports plan for future mitigation efforts and outside factors like climate change. Requires extensive initial data and could take over a year to start.
Invest in Terrestrial Carbon Sinks	Reforestation or afforestation is used to improve CO2 uptake and have a positive effect on the local natural environment	The mitigation strategy has relatively little cost, but the turnaround time on the investment is long
Support Modernization of Air Traffic Management (ATM)	The purchase and installation of new operational management system to better control aircraft movement and improve fuel usage	The FAA is funding new ATM system development, not airport operators. New systems may be limited by airport, airline or aircraft adaptation

Implement Emission-based Incentives and Landing Fees	Incentive fees are used to promote transitioning away from older and higher emitting aircraft technology	Airport would see increased revenue due to GHG emissions reductions. Turnaround time on investment is long due to infrequency of fleet turnover
Use Greenhouse Gas Impact Evaluations as Decision-Making Criteria	GHG emissions resulting from future projects alternatives and equipment purchases will be used as decision-making criteria	Evaluations often also highlight ways to optimize processes and reduce other environmental impacts. Data required to complete evaluations may be limited
Design Runways, Taxiways, Ramps & Terminals to Reduce Aircraft Taxiing Distances	Reducing distances will reduce associated fuel burn, thereby reducing GHG emissions	Fuel burn reductions will have other positive environmental impacts. Existing airports may be limited by space. Also NEPA compliance might be triggered by certain projects
Support Single/Reduced Engine Taxiing	Use of single engine or reduced engine power during aircraft taxiing is encouraged to reduce fuel burn and resulting GHG emissions	Reduced fuel burn would have additional positive environmental impacts. Airports cannot require these procedures but can instead seek voluntary implementation from airlines.
Develop an Airport Expansion and Development Greenhouse Gas Emission Policy	Limits are set for GHG emissions related to specific airport projects.	In California, a GHG assessment is already required for projects requiring an environmental impact report. Plans can be difficult to enforce and goals can be difficult to quantify
Minimize the Use of Auxiliary Power Units (APUs)	Gate power and pre-conditioned air are used to reduce aircraft fuel burn and associated GHG emissions	Direct savings are seen from a reduction in jet fuel expenses. Could take a long time to implement due to necessary airline engagement
Conduct Regular Greenhouse Gas (GHG) Emission Inventories	GHG inventories are conducted to create a baseline of emissions and monitor GHG reductions over time.	The largest GHG sources would be identified and benefits of GHG reduction projects would be quantified. Data collection can be time consuming
Create Partnerships with Intercity Rail Services to Optimize Passenger and Cargo Movement	Partnership would replace short-haul flights with more fuel efficient rail trips	Initial airline revenue would be negatively affected, but airlines would save money by eliminating shorter, low-demand routes. Successful reduction is contingent on passenger buy-in.

It should be noted that controlling specific airline aircraft operations is difficult for airport operators, as they often have little or no control over individual gate operations. While not all of the GHG mitigation strategies identified in Table 7 deal directly with reducing aircraft GHG emissions, they all present a way to reduce or counteract the impact of these aircraft emissions. The Bay Area airport section in the Introduction of this report identified the current strategies being used at each airport to reduce aircraft GHG emissions.

The strategies presented in Table 7 can be broken down into three categories:

1. <u>Planning Strategies</u> – This includes strategies such as developing a CAP, using GHG impact as decision making criteria, optimizing departure management, and conducting regular GHG emissions inventories. These strategies deal with the GHG emissions of the entire airport, but take into account the impact LTO GHG emissions have on the airport. These often don't involve physical changes to the airport. They also have the least amount of capital investment and the shortest time to initiate. They do, however, take involvement from many stakeholders at the airport and the return on investment is difficult to estimate.

2. <u>Airport Development Strategies</u> – This category includes strategies such as airfield layout design, runway and taxiway reduction, and updating airport gates to minimize the use of APUs. These strategies deal with specific updates and modernization to the airport. They often have a large capital investment, take a long time to implement, and are often dependent on the restrictions of a specific airport. They do, however, have the largest reduction potential on GHG emission reduction.

3. Economical Strategies – This category includes strategies such as developing carbon offsets, purchasing carbon offsets, and implementation of emissions-based landing fees. These strategies deal with monetary quantification of GHG emissions. They create a ways to prioritize airport upgrades from an economical perspective. The revenue produced from these strategies can be used to invest into airport developments that will help reduce GHG emissions. They take minimal capital to implement, but their return on investment in unclear and is highly dependent on a volatile global market.

Each of the airports should look at the strategies identified in Table 7 in order to prioritize their next mitigation projects. The LTO cycle represents a significant component of airport GHG emissions as previously identified. As funds become available for new environmental projects, they should be allocated to implementing some of the before mentioned mitigation strategies in order to have the greatest impact on reducing the airports total GHG emissions inventory.

It is also recommended that each airport conduct regular GHG emissions inventories to keep track of their progress in GHG reduction and their selected mitigation strategy effectiveness. SFO conducted an estimation of their carbon footprint as part of their 2012 climate action plan; however, in it they calculated LTO aircraft emissions by estimating the jet fuel use for one day, multiplying it by 365 and adjusting for a peak month factor (SFO 2012). The difference between the emissions noted in the Climate Action Plan and those calculated in this report are shown in Table 8.

Table 8
SFO LTO Cycle GHG Emissions Inventories (Metric Tons)

Report	2011	2012
SFO FY2012 CAP	579,105	685,095
Norton (2014)	495,239	512,588

As indicated in Table 8, SFO has over-estimated their GHG emissions by 17% in 2011 and 34% in 2012. This has an effect on SFO's GHG reporting and subsequent mitigation efforts. SFO did not use the emissions inventory method outlined in IPCC Good Practice and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2001) and instead used a cruder, but much faster calculation that requires far less data. However, this method does not account for variation from standard norms throughout the year and instead relies on a peak month adjustment factor. As indicated in the analysis of Figure 10 earlier in this section, the exact aircraft type emissions are needed to accurately produce an emissions inventory. SFO has indicated that emissions from the airlines, such as jet fuel consumption from aircraft in the LTO cycle is not a focus of their Climate Action Plan since it is not controlled by the Airport Commission, and therefore not as thoroughly analyzed. SFO should implement a more detailed method, similar to the one utilized in this report, to calculate their GHG emissions inventories in the future. These new inventories should be included in future climate action plans. It would enable them to further evaluate where their emissions sources are coming from throughout the year and produce a more accurate emissions inventory.

Because of SFO's size and existing GHG reduction efforts, it should look at all three strategies for potential mitigation strategies. However, the econmonical strategies category would be the easiest to implement and have the largest impact on the LTO GHG emissions. The Development Strategies are hard to implement based on the airport size and space restrictions in the surrounding area. Many of the strategies in the Planning Strategies category are already being implemented by the airport.

As a growing airport undergoing recent development and receiving new governmental funding, SJC should focus on mitigation strategies from the Airport Development Strategies section. Compared to other airports in this study, SJC has more growth potential and should consider GHG emissions from all phases of air travel, in their development projects.

OAK should implement LTO GHG emissions into their city CAP. By omitting them from their city GHG emissions inventory, they are missing a key emissions source and overall GHG mitigation potential. The other strategies in the Planning Strategies section should be used to help focus the existing environmental efforts of the City of Oakland on all large sources of GHG emissions, including LTO GHG emissions.

Conclusions

The Bay Area has three large to medium sized international airports that each have a significant impact on the environment. As noted in figure 5, the transportation industry makes up a large portion of global anthropogenic GHG emissions sources. By quantifying the exact emissions that these airports have on the local environment, the exact areas that should be focused on can be highlighted. At all airports studied, CO_2 emissions represented the overwhelming majority of impact in terms of GWP. Operational strategies to mitigate emissions should specifically target CO_2 reductions compared to of GHGs.

SFO contributes the majority of GHG emissions from aircraft in the LTO phase in the Bay Area. Due to the higher emissions and traffic volume, operational mitigation strategies conducted there should be more focused on total reduction than on cost. SFO has set in place a Climate Action Plan and has undergone gate renovations to reduce local GHG emissions as noted in the Bay Area Airports section. SFO should focus on the larger operational strategies noted in Table 7, such as carbon offset programs and emissions-based landing fees. These will have a larger impact on emissions and do not conflict with the spatial restrictions SFO faces.

OAK does not have as much emissions volume as SFO, but is still a large GHG producer. OAK has implement some airport renovations to reduce GHG emissions at several of the gates; however the City of Oakland has not incorporated the aircraft GHG emissions as part of its Climate Action Plan. OAK should implement the more planning focused strategies described in Table 7, such as conducting regular GHG emissions inventories and using GHG impact as a part of their decision making strategies, in addition to incorporating OAK in the City of Oakland's Climate Action Plan.

SJC has the smallest volume of emissions in the airports evaluated in this study, but has proven that they are growing. SJC has utilized the VALE program to fund many GHG reduction efforts including undergoing runway construction. SJC should further evaluate the strategies that are listed in Table 7. As SJC is beginning to have a stronger presence in Bay Area air travel, they should especially consider strategies that involve airport construction, such as evaluating airfield design and reducing taxiing distances, before their implementation gets more difficult with increasing air traffic.

Acknowledgements

I'd like to acknowledge both Professor Chris Ruehl and Maggie Winslow and MSEM Program director Stephanie Ohshita for their help and guidance on this research project. The work completed by the FAA's ACRP was critical in developing operational best practice recommendations. I would like to acknowledge the work done by all three Bay Area airports, on which this paper was based. I would also like to thank the remaining USF faculty that taught me the skills that I used on this master's project. I would also like to thank Stanford University for their support and generous contributions to my education and research. Lastly I'd like to thank my loved ones for their love and support throughout my studies.

References

Airbus (2014). A320 Dimensions and Key Data. http://www.airbus.com/aircraftfamilies/passengeraircraft/a320family/a320/specifications/

Boeing 737 (2014) 737 Family Technical Information. http://www.boeing.com/boeing/commercial/737family/specs.page?

Boeing 777 (2014) 777 Family Technical Information. http://www.boeing.com/boeing/commercial/777family/specs.page?

CDM & Synergy Consultants, Inc (2012) ACRP Report 56: Handbook for considering practical greenhouse gas emission reduction strategies for airports (No. ACRP Project 02-10).

City of Oakland (2012). City of Oakland Energy and Climate Action Plan.

City of San Jose (2011). Norman Y. Mineta San Jose International Airport Master Plan Update Project, San Jose, CA, Ninth Addendum to the Environmental Impact Report.

Climate Registry (2014). 2014 Climate Registry Default Emissions Factors.

EPA (2012). Air and Radiation, National Ambient Air Quality Standards. http://www.epa.gov/air/criteria.html

FAA (1997). Air Quality Procedures for Civilian Airports and Air Force Bases

FAA (2005). Aviation & Emissions: A Primer. Office of Environment and Energy

FAA (2012). Airport Categories – Airports.

Gil, M., W. Yan (2013). Is environmental innovation worth it? The case of the civil aviation industry of emerging markets, *AMPS 2013, Part II, IFIP AICT*. **415**, 294-301.

Gossling, S., G. Dubois, P. Peeters, W. Strasdas (2007). Volentary carbon offsetting schemes for aviation: efficiency, credibility and sustainable tourism. *Journal of Sustainable Tourism*. **15**, 3, 223-248.

IATA (2013). Air Transport Market Analysis: December 2012.

IPCC TAR WG3 (2001), Metz, B.; Davidson, O.; Swart, R.; and Pan, J., ed., Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, ISBN 0-521-80769-7.

IPCC (2001). Good practice and guidance and uncertainty management in national greenhouse gas inventories. IPCC, Geneva, Switzerland.

IPCC (2006). IPCC, Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy, Chapter 3: Mobile Combustion, Table 2.7.

IPCC (2007). Climate Change 2007: Synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 104pp.

KB Environmental Sciences, Inc., Environmental Science Associates, Inc., Synergy Consultants, Inc. & Stonefield Environmental Consulting (2013). ACRP Report 84: Guidebook for preparing airport emissions inventories for state implementation plans (No. ACRP Project 02-21).

Kim, B., I. Waitz, M. Vigilante, R. Bassarab (2009) ACRP Report 11: Guidebook on preparing airport greenhouse gas emissions inventories (No. ACRP Project 02-06).

Los Angeles International Airport (2013). LAX Specific Plan Amendment Study, Final EIR.

Macintosh, A., L. Wallace (2009). International Aviation Emissions to 2025: Can emissions be stabilized without restricting demand? Energy Policy. 37, 264-273.

Maurice, L. Q., H Lander, T Edwards, W.E Harrison III (2001) Advanced aviation fuels: a look ahead via a historical perspective. Fuel, 80 (5), 747-756, ISSN 0016-2361,

Metropolitan Airports Commission (2010). Greenhouse Gas Report. Minneapolis, MN.

Mineta San Jose International Airport (2014). Facts: Silicon Valley's Airport. http://www.flysanjose.com/fl/about/newsroom/AirportStats.pdf

OAK (2014). Oakland International Airport: Air Quality and Alternative Fuels.

Oakland Airport (2014). Year-end Airport Statistics Summary. http://oaklandairport.com/airport_stats_yearend_stats.shtml

Olsthoorn, X. (2001). Carbon dioxide emissions from international aviation: 1950–2050. Journal of Air Transport Management, 7(2), 87-93.

Peeters, Paul, E. Szimba, M. Duijnisveld (2005). European tourism transport and environment. Association for European Transport and contributors.
Port Authority of New York & New Jersey (2010). Greenhouse Gas and Criteria Air Pollutant Emission Inventory for the Port Authority of New York & New Jersey. New York, NY.

SFO (2011). Environmental Sustainability Report

SFO (2012). FY2012 Climate Action Plan

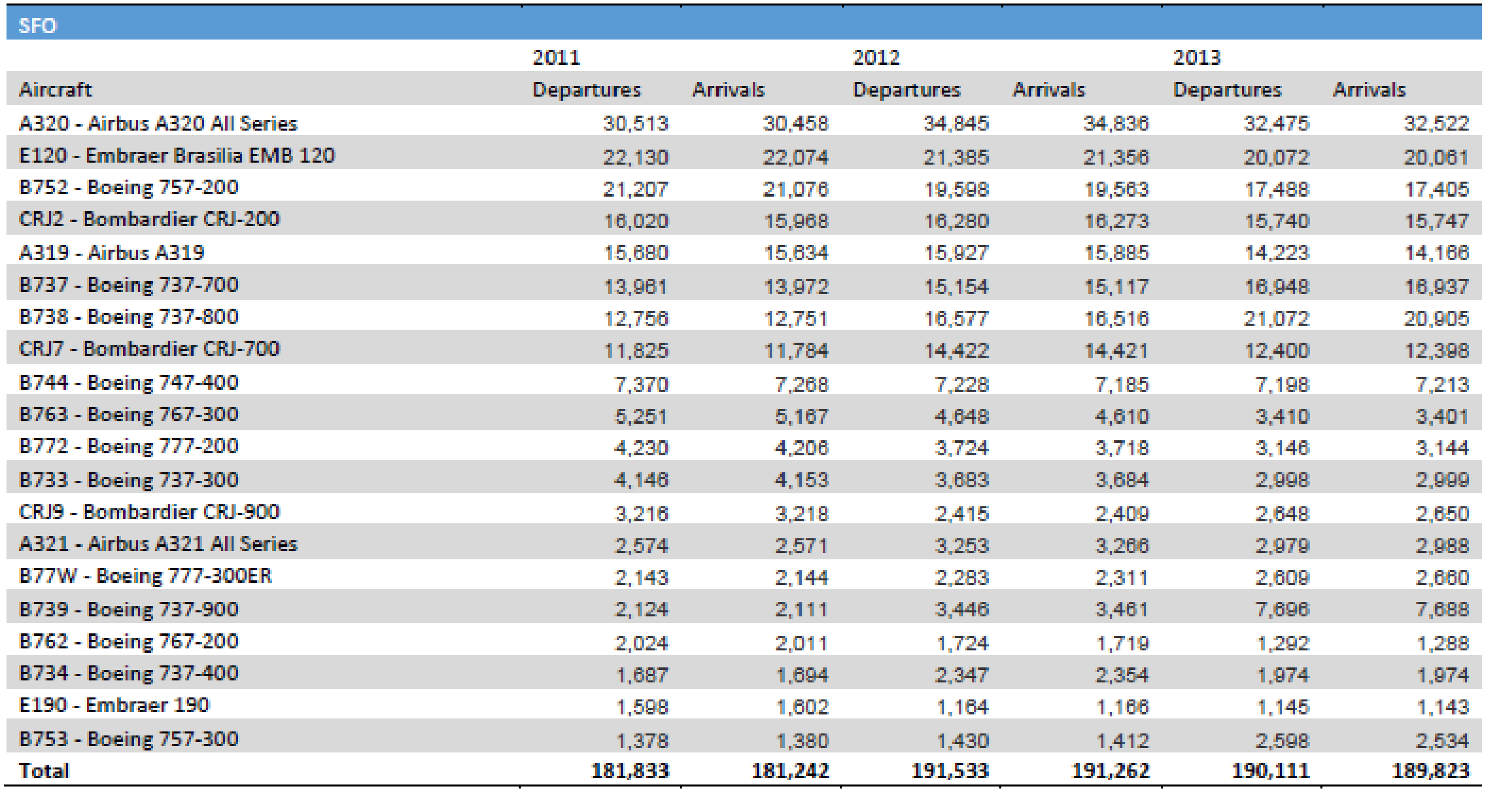
Song, S., & Shon, Z. (2012). Emissions of greenhouse gases and air pollutants from commercial aircraft at international airports in Korea. Atmospheric Environment, 61(0), 148-158.

San Francisco International Airport (2012). Welcome to SFO. http://media.flysfo.com.s3.amazonaws.com/pdf/about/brochures/sfowelcomebrochure.pdf

United States Department of Transportation (2012). Table 1-44: Passengers Boarded at the Top 50 U.S. Airports (a). Research and Innovative Technology Administration, Bureau of Transportation Statistics.

Wuebbles, D., Gupta, M., & Ko, M. (2007). Evaluating the impacts of aviation on climate change. Eos, Transactions American Geophysical Union, 88(14), 157-160.

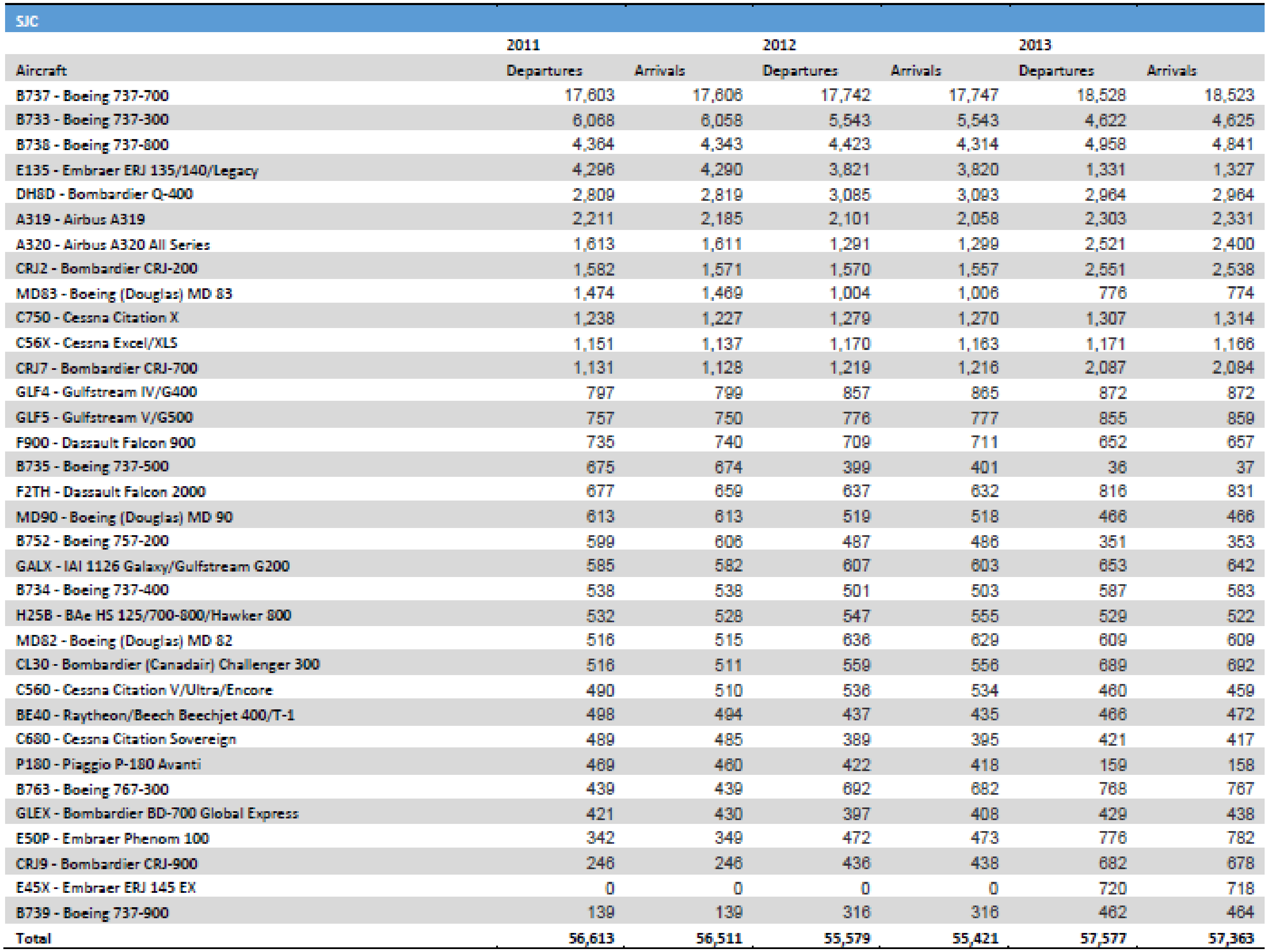
Appendix A



SFO						
	2011		2012		2013	
Aircraft	Departures	Arrivals	Departures	Arrivals	Departures	Arrivals
A320 - Airbus A320 All Series	30,513	30,458	34,845	34,836	32,475	32,522
E120 - Embraer Brasilia EMB 120	22,130	22,074	21,385	21,356	20,072	20,061
B752 - Boeing 757-200	21,207	21,076	19,598	19,563	17,488	17,405
CRJ2 - Bombardier CRJ-200	16,020	15,968	16,280	16,273	15,740	15,747
A319 - Airbus A319	15,680	15,634	15,927	15,885	14,223	14,166
B737 - Boeing 737-700	13,961	13,972	15,154	15,117	16,948	16,937
B738 - Boeing 737-800	12,756	12,751	16,577	16,516	21,072	20,905
CRJ7 - Bombardier CRJ-700	11,825	11,784	14,422	14,421	12,400	12,398
B744 - Boeing 747-400	7,370	7,268	7,228	7,185	7,198	7,213
B763 - Boeing 767-300	5,251	5,167	4,648	4,610	3,410	3,401
B772 - Boeing 777-200	4,230	4,206	3,724	3,718	3,146	3,144
B733 - Boeing 737-300	4,146	4,153	3,683	3,684	2,998	2,999
CRJ9 - Bombardier CRJ-900	3,216	3,218	2,415	2,409	2,648	2,650
A321 - Airbus A321 All Series	2,574	2,571	3,253	3,266	2,979	2,988
B77W - Boeing 777-300ER	2,143	2,144	2,283	2,311	2,609	2,660
B739 - Boeing 737-900	2,124	2,111	3,446	3,461	7,696	7,688
B762 - Boeing 767-200	2,024	2,011	1,724	1,719	1,292	1,288
B734 - Boeing 737-400	1,687	1,694	2,347	2,354	1,974	1,974
E190 - Embraer 190	1,598	1,602	1,164	1,166	1,145	1,143
B753 - Boeing 757-300	1,378	1,380	1,430	1,412	2,598	2,534
Total	**181,833**	**181,242**	**191,533**	**191,262**	**190,111**	**189,823**

OAK

	2011		2012		2013	
Aircraft	Departures	Arrivals	Departures	Arrivals	Departures	Arrivals
B737 - Boeing 737-700	24,860	24,873	26,067	26,042	25,220	25,202
B733 - Boeing 737-300	10,317	10,296	8,498	8,494	8,028	8,036
A319 - Airbus A319	3,206	3,190	2,384	2,353	2,332	2,258
A320 - Airbus A320 All Series	2,736	2,732	2,757	2,751	3,134	3,126
MD11 - Boeing (Douglas) MD 11	2,348	2,341	2,223	2,217	2,067	2,069
C208 - Cessna 208 Caravan	1,985	2,003	1,959	1,977	1,995	2,014
A306 - Airbus A300 B4-600	1,858	1,864	1,754	1,751	1,609	1,605
PA31 - Piper Navajo PA-31	1,813	1,635	1,064	1,020	60	30
B738 - Boeing 737-800	1,659	1,637	2,514	2,446	3,425	3,327
DC10 - Boeing (Douglas) DC 10-10/30/40	1,522	1,534	1,639	1,648	1,650	1,652
DH8D - Bombardier Q-400	1,515	1,511	1,635	1,632	1,233	1,234
CRJ2 - Bombardier CRJ-200	1,296	1,301	1,042	1,042	36	32
B735 - Boeing 737-500	1,240	1,238	882	884	33	32
B763 - Boeing 767-300	836	819	1,196	1,191	1,413	1,414
BE99 - Beech Airliner 99	791	796	427	440	30	23
C750 - Cessna Citation X	619	609	657	655	738	735
GLF4 - Gulfstream IV/G400	574	565	635	627	643	638
E135 - Embraer ERJ 135/140/Legacy	549	549	575	561	504	488
B752 - Boeing 757-200	543	551	726	731	731	731
SW4 - Swearingen Merlin 4/4A Metro2	517	562	452	486	9	7
CRJ7 - Bombardier CRJ-700	533	536	444	445	1,593	1,591
P180 - Piaggio P-180 Avanti	527	524	457	451	170	170
E50P - Embraer Phenom 100	511	509	448	450	598	593
H25B - BAe HS 125/700-800/Hawker 800	478	488	538	546	468	478
MD83 - Boeing (Douglas) MD 83	481	475	1,296	1,302	817	818
GLF5 - Gulfstream V/G500	471	466	420	416	510	514
PC12 - Pilatus PC-12	473	464	431	419	371	337
C56X - Cessna Excel/XLS	452	447	463	455	462	461
C560 - Cessna Citation V/Ultra/Encore	443	442	413	414	360	357
LJ35 - Bombardier Learjet 35/36	436	438	438	434	379	375
CL60 - Bombardier Challenger 600/601/604	442	428	536	532	508	508
CL30 - Bombardier (Canadair) Challenger 300	435	427	512	512	562	558
F900 - Dassault Falcon 900	414	415	484	472	446	444
BE40 - Raytheon/Beech Beechjet 400/T-1	344	336	287	285	331	331
BE20 - Beech 200 Super King	318	318	293	292	340	335
CRJ9 - Bombardier CRJ-900	298	298	1,788	1,793	1,383	1,388
C525 - Cessna CitationJet/CJ1	188	188	263	257	359	351
B77L - Boeing 777-200LRF/LR	1	1	69	70	348	349
F2TH - Dassault Falcon 2000	257	255	230	234	332	325
Total	**68,286**	**68,061**	**68,896**	**68,727**	**65,227**	**64,936**



SJC						
	2011		2012		2013	
Aircraft	Departures	Arrivals	Departures	Arrivals	Departures	Arrivals
B737 - Boeing 737-700	17,603	17,606	17,742	17,747	18,528	18,523
B733 - Boeing 737-300	6,068	6,058	5,543	5,543	4,622	4,625
B738 - Boeing 737-800	4,364	4,343	4,423	4,314	4,958	4,841
E135 - Embraer ERJ 135/140/Legacy	4,296	4,290	3,821	3,820	1,331	1,327
DH8D - Bombardier Q-400	2,809	2,819	3,085	3,093	2,964	2,964
A319 - Airbus A319	2,211	2,185	2,101	2,058	2,303	2,331
A320 - Airbus A320 All Series	1,613	1,611	1,291	1,299	2,521	2,400
CRJ2 - Bombardier CRJ-200	1,582	1,571	1,570	1,557	2,551	2,538
MD83 - Boeing (Douglas) MD 83	1,474	1,469	1,004	1,006	776	774
C750 - Cessna Citation X	1,238	1,227	1,279	1,270	1,307	1,314
C56X - Cessna Excel/XLS	1,151	1,137	1,170	1,163	1,171	1,166
CRJ7 - Bombardier CRJ-700	1,131	1,128	1,219	1,216	2,087	2,084
GLF4 - Gulfstream IV/G400	797	799	857	865	872	872
GLF5 - Gulfstream V/G500	757	750	776	777	855	859
F900 - Dassault Falcon 900	735	740	709	711	652	657
B735 - Boeing 737-500	675	674	399	401	36	37
F2TH - Dassault Falcon 2000	677	659	637	632	816	831
MD90 - Boeing (Douglas) MD 90	613	613	519	518	466	466
B752 - Boeing 757-200	599	606	487	486	351	353
GALX - IAI 1126 Galaxy/Gulfstream G200	585	582	607	603	653	642
B734 - Boeing 737-400	538	538	501	503	587	583
H25B - BAe HS 125/700-800/Hawker 800	532	528	547	555	529	522
MD82 - Boeing (Douglas) MD 82	516	515	636	629	609	609
CL30 - Bombardier (Canadair) Challenger 300	516	511	559	556	689	692
C560 - Cessna Citation V/Ultra/Encore	490	510	536	534	460	459
BE40 - Raytheon/Beech Beechjet 400/T-1	498	494	437	435	466	472
C680 - Cessna Citation Sovereign	489	485	389	395	421	417
P180 - Piaggio P-180 Avanti	469	460	422	418	159	158
B763 - Boeing 767-300	439	439	692	682	768	767
GLEX - Bombardier BD-700 Global Express	421	430	397	408	429	438
E50P - Embraer Phenom 100	342	349	472	473	776	782
CRJ9 - Bombardier CRJ-900	246	246	436	438	682	678
E45X - Embraer ERJ 145 EX	0	0	0	0	720	718
B739 - Boeing 737-900	139	139	316	316	462	464
Total	**56,613**	**56,511**	**55,579**	**55,421**	**57,577**	**57,363**

Table 4
Typical LTO Emissions for Aircraft Type (Climate Registry 2014)

Aircraft	CO2 (kg/LTO)	CH4 (kg/LTO)	N2O (kg/LTO)
A300	5450	0.12	0.2
A310	4760	0.63	0.2
A319	2310	0.06	0.1
A320	2440	0.06	0.1
A321	3020	0.14	0.1
A330-200/300	7050	0.13	0.2
A340-200	5890	0.42	0.2
A340-300	6380	0.39	0.2
A340-500/600	10660	0.01	0.3
707	5890	9.75	0.2
717	2140	0.01	0.1
727-100	3970	0.69	0.1
727-200	4610	0.81	0.1
737-100/200	2740	0.45	0.1
737-300/400/500	2480	0.08	0.1
737-600	2280	0.1	0.1
737-700	2460	0.09	0.1
737-800/900	2780	0.07	0.1
747-100	10140	4.84	0.3
747-200	11370	1.82	0.4
747-300	11080	0.27	0.4
747-400	10240	0.22	0.3
757-200	4320	0.02	0.1
757-300	4630	0.01	0.1
767-200	4620	0.33	0.1
767-300	5610	0.12	0.2
767-400	5520	0.1	0.2
777-200/300	8100	0.07	0.3
DC-10	7290	0.24	0.2
DC-8-50/60/70	5360	0.15	0.2
DC-9	2650	0.46	0.1
L-1011	7300	7.4	0.2
MD-11	7290	0.24	0.2
MD-80	3180	0.19	0.1
MD-90	2760	0.01	0.1
TU-134	2930	1.8	0.1

TU-154-M	5960	1.32	0.2
TU-154-B	7030	11.9	0.2
RJ-RJ85	1910	0.13	0.1
BAE 146	1800	0.14	0.1
CRJ-100ER	1060	0.06	0.03
ERJ-145	990	0.06	0.03
Fokker 100/70/28	2390	0.14	0.1
BAC111	2520	0.15	0.1
Dornier 328 Jet	870	0.06	0.03
Gulfstream IV	2160	0.14	0.1
Gulfstream V	1890	0.03	0.1
Yak-42M	2880	0.25	0.1
Cessna 525/560	1070	0.33	0.03
Beech King Air	230	0.06	0.01
DHC8-100	640	0	0.02
ATR72-500	620	0.03	0.02

Source: IPCC (2006)