ANALYSIS OF EMISSIONS INVENTORY FOR "SINGLE-ENGINE TAXI-OUT" OPERATIONS

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***Abstract*—Stringent federal and state programs along with technology innovation have resulted in declining emissions from static sources (e.g. power plants) and are projected to meet national quality standards by 2025. The same cannot be said for mobile sources of emissions from flight operations at airports. In the absence changes in airport operations, the forecast rates of growth in flight operations will jeopardize State's abilities to lower emissions to meet Federal standards.**

Recent studies indicate that 96% of flights in the U.S. accrue their delays at the airports and directly impact local non-attainment through emissions. This paper examines the sensitivity of emission factors (number of engines, engine efficiency and fleet mix, taxi-out time) through a case-study of departure operations at Orlando (MCO) and New York-LaGuardia. Under the assumptions of a representative fleet mix, departure schedule, runway assignment, and taxi flows, "feasible single engine" taxi-out procedures reduced emissions (CO/NOx/SOx/HC) by 27% at MCO and 45% at LGA. To achieve the same level of emissions reduction requires a 25% decrease in taxi-out time at MCO, and 44% decrease at LGA. The implications of these results on optimization of surface operations to minimize emissions are discussed.

Keywords-component; emissions, noise, surface optimization,single engine, taxi, fuel, pollution, environment.

I. INTRODUCTION

Flight operations result in the emission of a host of air pollutants that adversely affect public health and the environment. Nitrogen Oxides (NOx) and Hydrocarbons (HC) are precursor emissions of ground-level ozone, which causes lung irritation and aggravates diseases such as asthma, chronic bronchitis, and emphysema. Particulates have adverse cardiopulmonary effects and contribute to regional environmental problems such as haze and acid rain. Toxics such as benzene and formaldehyde are known or probable human carcinogens.

Stringent Federal and State regulatory programs, along with innovations in technology, have resulted in significant reductions in projected emissions from static sources (e.g. power plants) by 2025 to meet Federal standards (Cooper et al, 2003, page I-6). Despite improvements in aircraft engine technologies, the forecast growth in flight operations will yield large increases in airport emissions. These emissions are projected to jeopardize the ability of States in non-attainment of criteria pollutant National Ambient Air Quality Standards (NAAQS) from meeting Federal ambient levels of these pollutants.

Recent studies indicate that 96% of flights in the U.S. accrue delays at the airports as opposed to airborne delays (Xu, 2007; Chappell, 2004). These delays are the result of carrier delays (i.e. gate push-back), delays that are the result of departures scheduled in excess of the departure capacity of the airport (i.e. departure congestion), delays that are the result of predicted airborne delay (e.g. Miles-In-Trail, Airspace Flow Program), and destination airport delays (Ground Delay Program).

These delays, contribute to local emissions in excess of the ambient emissions from non-delayed operations at the airport. This paper examines the sensitivity of emission factors (number of engines, engine efficiency and fleet mix, and taxi-out time) through a case-study of departure operations at Orlando (MCO) and New York-LaGuardia. Under the assumptions of representative fleet mix, departure schedule, runway assignment, and taxi flows, the following results were identified:

- "Single Engine" taxi-out procedures have the potential to reduce emissions (CO/NOx/SOx/HC) by 27% at MCO.
- "Single Engine" taxi-out procedures have the potential to reduce emissions (CO/NOx/SOx/HC) by 45% at LGA
- To achieve the same level of CO/NOx/SOx/HC reductions as "single engine" operations, would require an average of 27% (27, 26, 22, 24)% decrease in taxi-out time at MCO
- To achieve the same level of CO/NOx/SOx/HC reductions as "single engine" operations, would require an average of 44% (46, 45, 43, 44)% decrease in taxi-out time at LGA.

The paper is organized as follows: Section 2 provides an overview of aircraft emissions. Section 3 describes the method of analysis. Section 4 describes the results of the analysis. Section 5 the implications of these results on optimization of

This Research has been funded by NASA Ames under project MEFISTO

ISBN: 978-0-615-20720-9

surface operations to minimize emissions and on the design of an Airport Environmental Dashboard are discussed.

II. AIRCRAFT EMISSIONS AND MITIGATION STRATEGIES

The total emissions burden associated with airport operations is the result of emissions from aircraft, Ground Support Equipment (GSE), Ground Access Vehicles (GAV), stationary sources, and private vehicles (Cooper, Ulbrich 2003). Figure 1 illustrates the contribution of each of these sources to NOx emissions at Logan airport in 1999.

A. Chemistry of Emissions:

Oxidation of fuel can be represented by the following chemical reaction

$$\underbrace{CnHm + S}_{\text{Fuel}} + \underbrace{N_2 + O_2}_{\text{Air}} \rightarrow \underbrace{CO_2 + H_2O + N_2 + O_2}_{\text{Products of Ideal Combustion}} + \underbrace{NOx + CO + SOx + Soot + UHC}_{\text{Products of Non-ideal Combustion}}$$

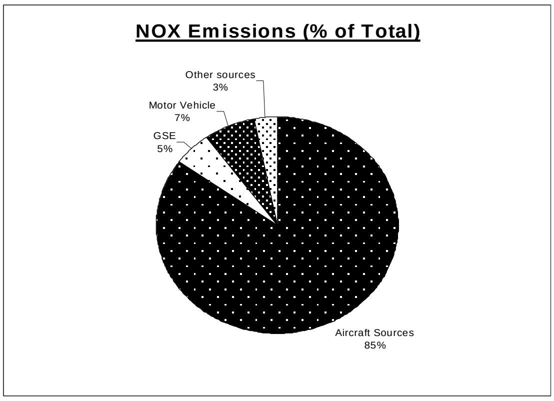

Figure 1 – Contribution of sources of emissions to total NOx emissions at Logan International in 1999.

National Ambient Air Quality Standards

Pollutant	Primary Stds.	Averaging Times	Secondary S
Carbon Monoxide	9 ppm ($10\ mg/m^3$)	8-hour	None
	35 ppm ($40\ mg/m^3$)	1-hour	None
Nitrogen Dioxide	0.053 ppm ($100\ \mu g/m^3$)	Annual (Arithmetic Mean)	Same as Pri
Sulfur Oxides	0.03 ppm	Annual (Arith. Mean)	-------
	0.14 ppm	24-hour	-------
	-------	3-hour	0.5 ppm ($1300\ \mu g/m^3$

Table 1- NAAQS Source- http://www.epa.gov/air/criteria.html

Aircraft fuel is a mixture of hydrocarbons (essentially kerosene) and sulphur. Its combustion in the presence of oxygen and atmospheric nitrogen (inert), produces several products. Some of the products, i.e. carbon dioxide, water, left over nitrogen and oxygen are products of ideal combustion and non-harmful to the environment. However, not all of the fuel undergoes ideal combustion, resulting in harmful by-products like nitrous oxides, sulphur oxides, carbon monoxide, and unburned hydrocarbons.

B. Permissible safe level of the pollutants

The Environmental Protection Agency (EPA), under the influence of Clean Air Act, has set National Ambient Air Quality Standards for pollutants considered harmful for public health and the environment. National Ambient Air Quality Standards for six principal pollutants, known as 'criteria' pollutants, are listed in Table 1. The units of measure for the standards are parts per million (ppm) by volume, milligrams per cubic meter of air (mg/m^3), and micrograms per cubic meter of air ($\mu g/m^3$).

Although most US airports are well within the National Ambient Air Quality Standards (NAAQS) set by EPA (Environmental Protection Agency), some of the airports fall in the non-attainment zone for ozone for non-compliance with NAAQS: For example, the state of Texas has four areas that are out of compliance with the NAAQS for ozone, two of which -- Houston-Galveston-Brazoria and Dallas/Forth Worth -- are also home to major airport facilities. The Houston-Galveston-Brazoria non-attainment area alone hosts three major commercial airports: (1) George Bush Intercontinental, (2) William P. Hobby, and (3) Ellington Field. The Dallas/Fort Worth non-attainment area is also host to four commercial airports: (1)Dallas/Fort Worth International (2) Fort Worth Alliance; (3) Meacham; and (4) Dallas Love Field. Several airports, including Sacramento International Airport (SMF), are located in the Sacramento area of California, which is classified as being in severe non-attainment of the ozone NAAQS. (see Cooper, Ulbrich 2003, pg IV -16 for details)

C. Mitigating Aircraft Emissions

There are two approaches to mitigating aircraft emissions for airport operations (Figure 2). The first approach involves improvements in the technology (aircraft engines, fuel, and aircraft design). The second approach is related to modifying airport operations. The following discussion focuses on airport operations.

Emission mitigation strategies that do not involve changes to current engine technology or aircraft design include: (1) Decreasing Taxi-out time (TOT), (2) Lower Emission per passenger through Load Factor and Upguage, (3) Reducing Power Output during Taxi (see Cooper, Ulbrich 2003, pg III 7-10 for details)

(1) Decreasing Taxi-out time (TOT): Aircraft emissions of HC and CO tend to be particularly high during taxiing operations. Operational changes that reduce aircraft idling and taxi time

ISBN: 978-0-615-20720-9

directly reduce pollutant emissions. A possible option is

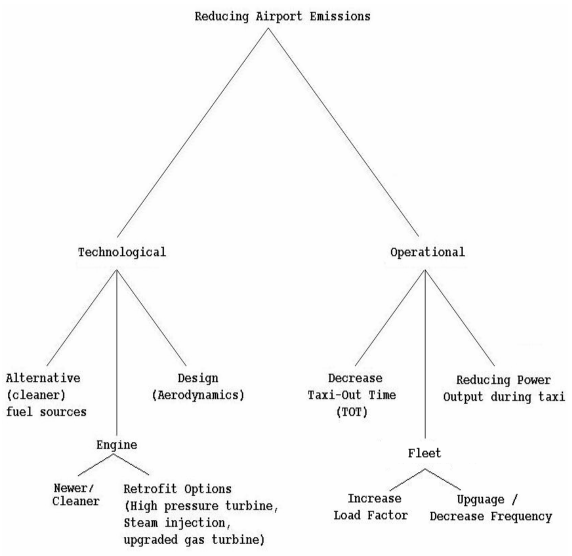

Figure 2: Mitigating Aircraft Emissions

"dispatch towing". High-speed tugs can be used to move aircrafts between the terminal gate and runway more efficiently and with fewer frequent stops than with standard practices. Such tugs have already been tested successfully by Virgin Atlantic at LAX and SFO. Taxi-times can also by reduced by planning the airport more efficiently. For example, using a decentralized gate designs wherein passengers are brought to and from the aircraft by other transport vehicles. Also, if better dynamic real time estimates of the taxi-out time were available to the airline and the ground controller, one could possibly hold the aircrafts at the gate (if possible) or ask the pilot to operate on fewer engines. There has been some promising work in this area recently.(Ganesan, Poornima 2008).

(2) Fleet: Airlines can improve their operational efficiency by maximizing the number of passengers on each flight, thereby minimizing emission per passenger. Airlines already have enough profit incentive to increase their "load factors". Upguaging is another approach: A single flight serving more passengers on a larger plane may reduce emissions – and airline costs – compared to multiple flights using smaller airplanes to serve the same route. However, other considerations often apply, such as the desire to provide the customers with more frequent flight options. Also, depending on how landing fees may be structured it might be more expensive to land one large airplane (weight based landing) compared to two smaller airplanes.

(3) Reducing Power Output during Taxi: Another way of reducing aircraft emission is more judicious use of aircraft engines in taxi mode. Most of the modern day aircraft are equipped with two to four engines, one or more of which can be shut down during taxiing. This not only reduces emissions, but allows other engines to operate more efficiently (i.e. at higher RPMs) resulting in lower consumption of fuel and less HC and CO emissions per pound of fuel consumed. Heathrow airport in the United Kingdom already encourages this practice. It should be noted that execution of "single engine ops" is at pilot discretion, as engines have their own warm up and cool down time when they achieve thermal stability.

III. METHOD FOR COMPUTATION OF ENVIRONMENTAL FACTORS FOR DEPARTURE

Estimates of emissions from aircraft can be computed using models developed by ICAO or FAA. The FAA model is known as the Emission and Dispersion Modeling System (EDMS) EDMS was developed by the FAA in cooperation with the U.S. Air Force in the mid 1980's as a complex source microcomputer model to assess the air quality impact of proposed airport development projects. EDMS is designed to include the contribution of airport emission sources, particularly aviation sources, which consists of aircrafts, auxiliary power units (APUs) and ground support equipments.

Emission is calculated using the following formula:

$$Emissions(grams) = TOT(\qquad)*EI(grams/kg)*$$
$$Fuel.Flow(kg/\min)*\#.Of.Engines$$

Each aircraft engine type has its own emission characteristic. Depending on the engine type levels of CO, NOx, SOx and HC (Hydro Carbon) emissions may vary. This information is comprehensively captured in what is called an Emission Index (EI). The Emission Index is a function of engine type, phase of flight (only taxi mode for our study) and pollutant (hence there is an EI corresponding to each category of pollutants NOX, SOX etc.). The emission indices are based on information provided by the engine manufacturers and documented by the FAA and ICAO (EPA, 1985) (Lang and Chin, 1998).

Row # 8 labeled NOX_EI_G_KG means that for every kilogram (1kg = 2.2 lbs) of fuel that B767 consumes, each of its 2 engine emits about 3.4 grams of NOx into the atmosphere. Other rows can be interpreted similarly.

Note: We used EDMS as a source of the aircraft Emission Indices. Even though EDMS is a FAA progeny and is widely accepted in the industry, there are some issues which are dealt better in an alternate model called NESCAUM (Northeast States for Coordinated Air Use Management). EDMS simplifies the air fleet mix. Only one (the most common) engine is assigned to each aircraft. However we know that each aircraft can be outfit with more than one engine types. For example: Boeing 757-200 can be fitted with 4 different types of engine. NESCAUM improves on EDMS by taking a weighted average of the different engine types used on each airline's fleet of aircraft. The same weighted average methodology is followed while calculating the emission indices for the APUs. Hence NESCAUM provides a finer and more accurate detail level than EDMS (Cooper, Ulbrich 2003).

IV. CASE STUDIES: LGA AND MCO

Case studies of Orlando (MCO) and New York –LaGuardia (LGA) were conducted to understand the factors that contribute to emissions. Analysis was done for the month of July 2007 for our case study.

ISBN: 978-0-615-20720-9

Taxi-out times and ETMS equipment number were extracted from the ASPM database (Aviation Safety Performance Metrics database maintained by the FAA) for individual take-off operations. This study only considered departure operations for our study.

ETMS_Name	B767
ETMS_Descr	Boeing Company B767/CF6-80A
Num_Engine	2
Fuel_Flow	0.150000006
Taxi_Fuel	0.150000006
CO_EI_G_KG	28.20000076
HC_EI_G_KG	6.28000021
NOX_EI_G_K	3.400000095
SOX_EI_G_K	1

Table 2 A sample row of EDMS/ICAO database showing Emission Index of B767s

The ETMS equipment number extracted from the ASPM database was then mapped to its corresponding Emission Index (EI) number in the EDMS (Emission and Dispersion Modeling System) database.

Some assumptions: (1) the study considered only ground operations. Future work will take into account the full Landing Take-off Cycle (LTO). (2) only considered aircraft pollution not Ground Service Vehicles etc. See Figure 1. (3) All aircrafts with the ETMS Equipment number were assumed to have the same engine type. This is the underlying principle behind ETMS emission estimating methodology.

A. Daily Emissions Profile

Emissions were estimated using the equations described in Section 3. Figure 3 shows the daily profile of emissions for MCO and LGA. The X axis is the time of day in 15 minute epochs. The Y axis is the pollutant emissions (i.e. CO, HC, NOx, SOx) weight in grams. The dotted line in each curve represents the cumulative emissions over the course of the day. Peak periods result in a steeper rise in the cumulative curve.

B. Monthly Emissions Profile

Figure 4 summarizes the monthly emission profile at MCO for July 2007. The histograms indicate the number of days with varying levels of cumulative emissions. The bars on the right indicate the days for which the emission level of a particular pollutant was higher than the rest. The 'bad' days are a result of higher taxi out times on those particular days (since the fleet mix operating at MCO is pretty much constant throughout).

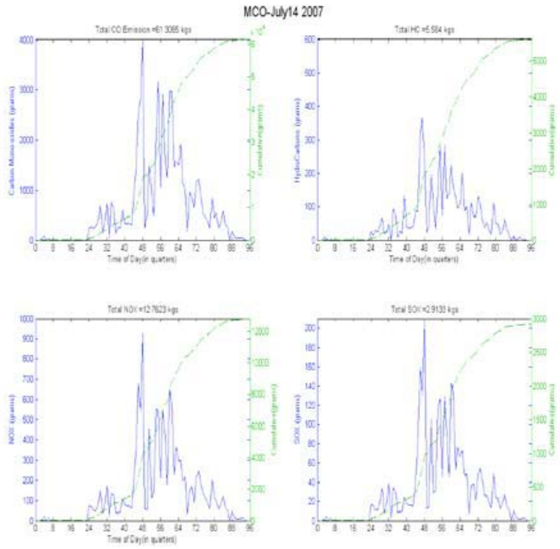

Figure 3(a)– Emissions on a typical day at MCO (July 14th, 2007)

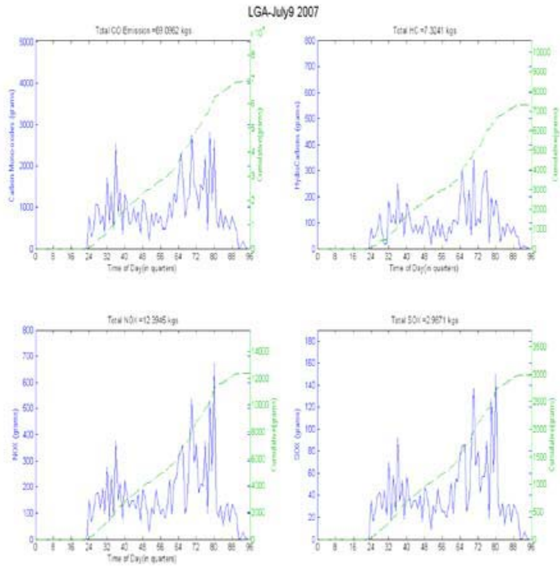

Figure 3(b) – A typical day at LGA (July 9th, 2007)

C. Comparison between MCO and LGA

Figure 5 provides the total emissions per day over the course of the month for each pollutant. The LGA emissions are greater than the MCO emissions except on Saturdays. Comparison between LGA and MCO- Operational and Fleet mix interplay

Figure 6 shows a comparison of the rate of emissions for each of the pollutants between MCO and LGA. The rate of emissions was derived from only weekday fleet mix and schedule for July 2007. The X-axis is the total taxi-out time.

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The Y-axis is the total pollutant level. The slope of the graph gives the rate of pollution metric tonnes/minute of taxi out time. A higher slope represents a higher polluting fleet independent of taxi time. The slope is a product of number of engines, fuel flow and emission index (for the particular category of pollutant).

The MCO fleet exhibits slightly higher average emissions for the three of the four pollutants than the LGA fleet. The total

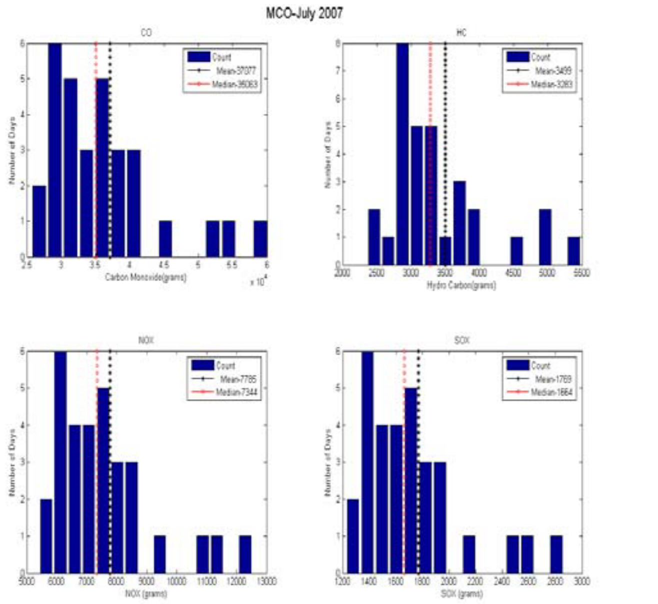

Figure 4(a) – Histogram for MCO showing CO, NOX, SOX and HC level for the month of July 2007.

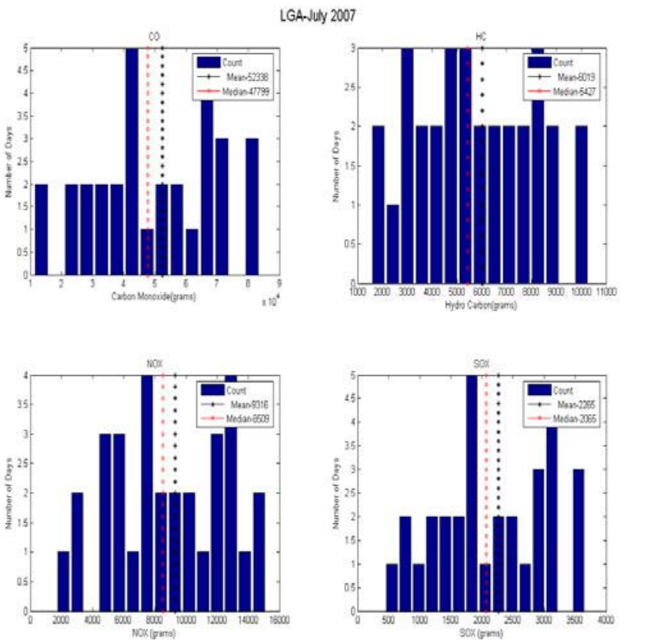

Figure 4(b) – Histogram for LGA showing CO, NOX, SOX and HC level for the month of July 2007.

daily emissions can be determined by reading up from the X-axis total daily taxi-out time to the rate-line and then reading across to the Y-axis to the total emissions.

D. Single Engine Taxi Operations

Taxi on reduced engines, such as a single engine for double engine aircraft, has the potential to reduce emissions by half. This practice is performed at some airports where emissions are a concern (e.g. London Heathrow Airport (LHR)). In practice, due to engine start-up and shut-down procedures, the single engine operations can only be used when taxi delays are anticipated to be in excess of 15 minutes.

Figure 7 illustrates the impact of single-engine taxi for taxi-out delays in excess of 15 minutes at MCO and LGA. Since taxi-out times are shorter at MCO, single-engine taxi-out resulted in an average reduction in emissions of 27%. CO/NOx/SOx/HC reductions of 27%, 26%, 22%, and 24%

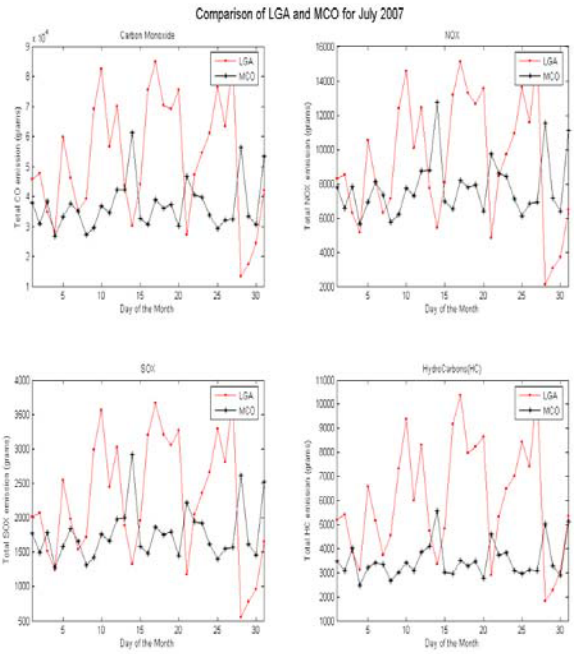

Figure 5 – Comparison of emissions at MCO and LGA for July 2007

respectively.

Single-engine taxi for taxi-out delays in excess of 15 minutes at LGA achieved an average reduction of 44%. CO/NOx/SOx/HC reductions of 46%, 45%, 43%, 44% respectively.

One of the main roadblocks with implementing a single engine taxi policy more stringently is the fact that engines typically require about 4-5 minutes of warm up time prior to take off to achieve thermal stability. It is counter productive to taxi on single engine and then wait at the runway trying to warm up the engines. In order to avoid such a situation one could use taxi out time prediction in issuing 'single engine taxi' advisories. A robust algorithm for Taxi out time prediction, which incorporates and captures the dynamic, stochastic nature of airport surface operations could help the Air traffic

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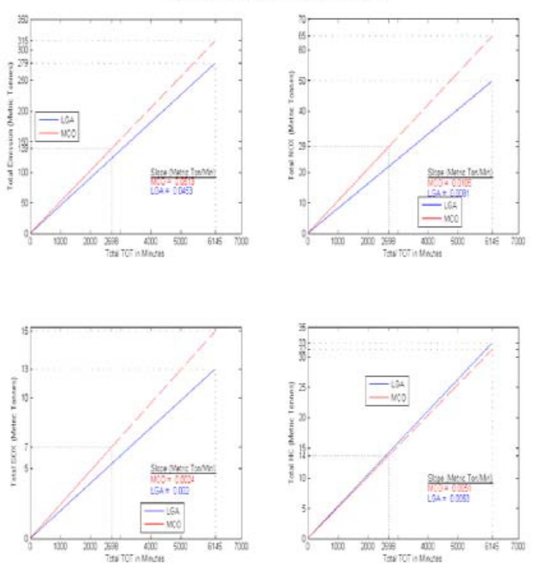

Figure 6 – Comparison of rate of emissions at MCO and LGA for July 2007

control and the airlines to make better decisions about whether or not they should issue a 'single engine taxi' advisory to the pilots. For example, if the Taxi out time is greater than certain threshold (say 15 min), one could advise the pilot to taxi out on a single engine for the first 8-10 minutes(depending on the confidence of prediction in Taxi Out time), and thus save on fuel and emissions.

V. CONCLUSIONS & FUTURE WORK

The paper examined the sensitivity of the factors contributing to emissions in taxi-out operations. The results indicate that under the constraint of a fixed-fleet, schedule, runway assignment procedures, and taxi-out operations, single-engine taxi provides the potential to reduce emissions up to approximately 44%. Under the constraints of a practical single-engine taxi procedure, that requires a minimum of 15 minutes taxi, the procedure provides the biggest advantage at airports with periods of delays in excess of 15 minutes.

Future Work:

(1) The ICAO/EDMS database that we referenced for obtaining engine emission characteristic is conservative in a sense that it assumes that all aircrafts with a given ETMS equipment number are fitted with the same engine type (the most common type). However it is not uncommon to have more than one engine types fit on the same aircraft type. NESCAUM improves on EDMS by taking a weighted average of different engine types used on each airline's fleet. Using this model in the future has a potential benefit of improving the accuracy of our emission computation

(2) Understanding and modeling the change in fuel flow while shifting to single engine taxi for different aircraft engine types would be helpful in estimating the benefits of a single engine taxi more accurately.

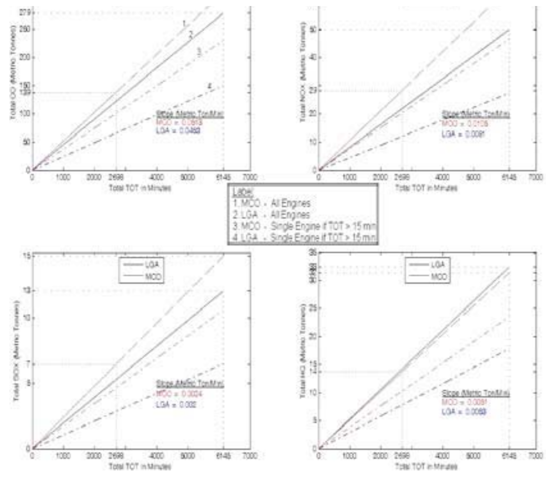

Figure 7: Effect of Single Engine Taxi

This model could then be used to obtain dollars gained (as a result of lesser fuel burnt) to incentivize the airlines.

(3) It is also required to understand the physical/operational constraints that prevent airlines/controller from adopting single engine taxi. For example:
- Engine warm up time to achieve thermal stability (3-5 minutes)
- No tight turns allowed on a single engine
- Abnormal weather conditions, i.e. Snow/ice
- Uneven ground surface at the airport.

ACKNOWLEDGMENT

This Research has been funded by NASA Ames under project MEFISTO (Modeling Environment Factors in Surface Traffic Optimization) and thanks are due to Gilena Monroe, Sandy Lozito, Len Tobias, John-Paul Clarke and Ed Knoesel(NYNJPA).

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