

1. Report No. SWUTC/03/167231-1		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Restricting the Use of Reverse Thrust as an Emissions Reduction Strategy				5. Report Date December 2001; revised July 2003	
				6. Performing Organization Code	
7. Author(s) Colin Rice and C. Michael Walton				8. Performing Organization Report No. Report 167231-1	
9. Performing Organization Name and Address Center for Transportation Research University of Texas at Austin 3208 Red River, Suite 200 Austin, Texas 78705-2650				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. 10727	
12. Sponsoring Agency Name and Address Southwest Region University Transportation Center Texas Transportation Institute Texas A&M University System College Station, Texas 77843-3135				13. Type of Report and Period Covered	
				14. Sponsoring Agency Code	
15. Supplementary Notes Supported by general revenues from the State of Texas.					
16. Abstract <p>As more metropolitan areas approach "non-attainment" status for ozone, air pollution at airports is becoming an increasingly important topic. Most proposed emissions reduction strategies target passenger automobiles and airport ground service equipment (GSE). At many airports, the future growth in oxides of nitrogen (NOx) emissions from aircraft is likely to offset any reduction achieved from GSE or passenger vehicles. In some metropolitan areas, airports may be responsible for as much as 10% of the regional NOx. As a result, other alternatives are needed for emissions reduction at airports.</p> <p>Reverse thrust is commonly used along with wheel brakes to slow aircraft during landing and occasionally to "power-back" aircraft away from a boarding gate. Currently, air pollution emissions generated during reverse thrust are not included in airport emissions inventories. Since the majority of aircraft NOx emissions occur off-airport during climbout and approach, reverse thrust can be responsible for an additional 15% or more of the on-airport NOx. This can create significant air quality impacts in the vicinity of the busiest airports. This research will attempt to quantify and model the air quality effect of NOx emissions produced during reverse thrust, using Dallas/Ft. Worth International Airport as a case study.</p>					
17. Key Words Emissions, Airport, Reverse Thrust, Air Pollution, Air Quality			18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161		
19. Security Classif.(of this report) Unclassified		20. Security Classif.(of this page) Unclassified		21. No. of Pages 118	22. Price



# **RESTRICTING THE USE OF REVERSE THRUST AS AN EMISSIONS REDUCTION STRATEGY**

by

Colin Rice

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Research Report SWUTC/03/167231-1

Combined final report for the following two SWUTC projects:  
Restricting the Use of Reverse Thrusts as an Emissions Reduction Strategy for Airports—  
167231 & Evaluating Operating Strategies and Transportation Control Measures which Reduce  
Air Pollution Emissions at Airports—473700-00063

Southwest Regional University Transportation Center  
Center for Transportation Research  
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Austin, TX 78712

December 2001  
revised July 2003



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## **ACKNOWLEDGMENT**

Support for this report was provided by a grant from the U.S. Department of Transportation, University Transportation Centers Program to the Southwest Region University Transportation Center which is funded 50% with general revenue funds from the State of Texas.

The authors would like to thank Dr. Michael McNerney, former Director of the Aviation Research Center at The University of Texas-Austin for his suggestions and ideas and the Airport Operations Staff at Austin-Bergstrom International Airport for enabling me to setup and collect data on the airfield.

The authors would also like to acknowledge the help of Dr. David T. Allen, Dr. Elena McDonald-Buller, and the staff at the UT Center for Energy and Environmental Resources for their assistance in the air quality modeling.



## **EXECUTIVE SUMMARY**

Air pollution associated with airports is becoming increasingly important as more metropolitan areas are violating the revised NAAQS for ozone. In some metropolitan areas, as much as 10% of the regional total emissions for NO<sub>x</sub> (oxides of nitrogen) can be attributed to activities associated with the airports. Reverse thrust is commonly used to help slow an aircraft during landing and occasionally to “power-back” away from boarding bridges. Currently, reverse thrust is not accounted for in airport emissions inventories. Since reverse thrust produces a significant amount of NO<sub>x</sub> over a relatively small area, its air quality effects can be significant.

### **BACKGROUND**

Aircraft are assumed to affect urban air quality only when they are inside the mixing layer, which is typically assumed to be under 3,000 feet. The current emissions computation methodology considers emissions from four modes of operation: landing, taxi, takeoff, and climbout. These operations are included in a landing-takeoff cycle (LTO). At present, there is no mode for reverse thrust.

Engine emissions factors have the units of grams of pollutant per kilogram of fuel burned. To compute aircraft emissions, the emissions factor for each mode is multiplied by the amount of fuel burned and by the number of engines. Fuel consumed during each phase is computed by multiplying the fuel burn rate by the times-in-mode (TIMs), which have been developed for each of the four modes of operation.

### **DATA COLLECTION**

In order to develop an emissions estimate for reverse thrust, data on reverse thrust usage was sampled at Austin/Bergstrom International Airport (ABIA). Experiments were designed to measure the amount of reverse thrust usage during landing and power-backing. The designs were based on the results of preliminary analyses, which showed that aircraft and airline type influenced thrust reverse usage greatest. A two-factor factorial design was selected as the experimental design and it was determined that a sample size of 624 observations was needed to obtain the desired level of precision. For power-backs, a sample size of 74 was needed, using a simple random.

Data collection stations were setup along both runways and behind American Airlines' gates at ABIA to observe thrust reverse usage. Since the camera could not be manned, a specially-designed data collection station was developed to record continuously for 8-hour intervals. Approximately 250 hours of video data were collected, containing 655 landings and 79 power-backs.

## **DATA ANALYSIS**

Analysis of variance was performed to isolate the factors influencing thrust reverse usage during landing. Based on the results of the data collection, a TIM for reverse thrust during landing should be 16.0 seconds for ABIA. The 95% confidence interval for reverse thrust usage ranged from 15.7 seconds to 16.3 seconds. Although some of the variation in thrust reverser usage during landing was explained by thrust reverser type, aircraft type, airline, and direction, the majority of the variation was influenced by other factors, which may not have been measured by this experiment.

During power-backing, reverse thrust was used for an average of 44 seconds.

## **FORECASTING**

In order to determine the emissions associated with the use of reverse thrust, the results of the data analysis were used to compute the quantity of additional aircraft NO<sub>x</sub> emissions. Since reverse thrust is not included in current aircraft emissions computations, a new mode of aircraft operation was added to the current methodology. A composite time-in-mode was developed, using the results of the results of the data analysis. An emissions factor which corresponds to the typical reverse thrust power setting was also selected.

Reverse thrust was found to have the largest impact at DFW Airport. This is because of the sheer number of aircraft operations and the practice of power-backing by American Airlines. In 2007, it was estimated that 1.2 tons per day of NO<sub>x</sub> would be emitted by the use of reverse thrust.

## **AIR QUALITY ANALYSIS**

Reverse thrust was found to increase DFW Airport's on-airport NO<sub>x</sub> emissions by 15%. Because emissions from reverse thrust are a small fraction of regional NO<sub>x</sub> emissions, they are

forecasted to have a minimal impact regional ozone levels. Their localized impact on ozone and nitrogen dioxide is more pronounced because of the significant concentration of additional nitric oxide (NO) produced. In this episode, the daily peak for ozone for the Dallas region is unaffected by reverse thrust. However, when the peak occurs near the airport or near CAMS70, reverse thrust could possibly have an effect. During ozone season 2001, CAMS70 recorded the highest frequency of 8-hour ozone standard violations. The airport NO<sub>x</sub> emissions may have in fact caused a reduction in the 8-hour average measured at CAMS70. Without the airport, CAMS70 may have produced the highest 8-hour average for the region.

The air quality analysis was performed using the Comprehensive Air Quality Model (CAMx), with the help of the UT Center for Energy and Environmental Resources. Model-ready input files were obtained from the Texas Natural Resource Conservation Commission. The grid cells containing DFW Airport were located and the NO<sub>x</sub> emissions in the cells were scaled up appropriately. Near the airport, reverse thrust was found to decrease ozone levels by as much as 11 ppb, while nitrogen dioxide (NO<sub>2</sub>) levels were increased by as much as 14 ppb, due to NO<sub>x</sub> titration. The peak NO<sub>2</sub> level for the region of 78 ppb was also found to occur at the airport.

## **CONCLUSION**

As a result of NO<sub>x</sub> scavenging, ozone levels were found to be decreased in the vicinity of the airport, while NO<sub>2</sub> levels were increased. The 14 ppb increase in NO<sub>2</sub> near the airport may significantly affect airport personnel, passengers, and nearby residents. DFW Airport handles 170,000 passengers daily and approximately 42,000 people are employed at the airport. (DFW Airport Board, 2001). The area affected by elevated levels of NO<sub>2</sub> attributed to reverse thrust covers approximately 112 square kilometers and it is estimated that 60,000 nearby residents may be affected.

Restricting the use of reverse thrust is an emissions reduction strategy which is easy to implement. Since restricting the use of reverse thrust does not require a costly capital investment, it has a very low cost per ton benefit. In lieu of mandating emissions reduction from GSE at DFW, airlines could be given a NO<sub>x</sub> emissions budget for their entire scope of operations. If their budget is exceeded, airlines could be charged a nominal fee for the amount emitted over the allowable quantity. The fee could be set according to the industry average cost of reducing NO<sub>x</sub>, currently estimated at \$10,000 per ton. Emissions reduction could then be achieved by the airlines using a variety or combination of measures.



## **ABSTRACT**

As more metropolitan areas approach “non-attainment” status for ozone, air pollution at airports is becoming an increasingly important topic. Most proposed emissions reduction strategies target passenger automobiles and airport ground service equipment (GSE). At many airports, the future growth in oxides of nitrogen (NO<sub>x</sub>) emissions from aircraft is likely to offset any reduction achieved from GSE or passenger vehicles. In some metropolitan areas, airports may be responsible for as much as 10% of the regional NO<sub>x</sub>. As a result, other alternatives are needed for emissions reduction at airports.

Reverse thrust is commonly used along with wheel brakes to slow aircraft during landing and occasionally to “power-back” aircraft away from a boarding gate. Currently, air pollution emissions generated during reverse thrust are not included in airport emissions inventories. Since the majority of aircraft NO<sub>x</sub> emissions occur off-airport during climbout and approach, reverse thrust can be responsible for an additional 15% or more of the on-airport NO<sub>x</sub>. This can create significant air quality impacts in the vicinity of the busiest airports. This research will attempt to quantify and model the air quality effect of NO<sub>x</sub> emissions produced during reverse thrust, using Dallas/Ft. Worth International Airport as a case study.



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## CHAPTER 1. INTRODUCTION

Reverse thrust is commonly used along with wheel brakes to slow aircraft during landing and to “power-back” aircraft away from a boarding gate. Currently, air pollution emissions generated during reverse thrust are not included in airport emissions inventories. During reverse thrust operation, the aircraft engines operate at a high power setting while their thrust is deflected forward by blocker doors which are introduced into the engine’s airflow.

Depending on runway conditions, exit locations, and landed weight, the duration of reverse thrust application during landing can be similar to a takeoff. The current emissions inventory methodology used for aircraft emissions does not contain a mode for reverse thrust. In most metropolitan areas, aircraft are responsible for 20-50% of the aviation-related NO<sub>x</sub> emissions (Rice and Walton, 2000). Therefore, it is likely that overall airport NO<sub>x</sub> emissions have been underestimated by at least 5-10% (Rice and Walton, 2000). Since the majority of aircraft emissions occur off-airport, it is estimated that reverse thrust will be responsible for as much as 15% of the on-airport NO<sub>x</sub> in the future. This is projected to cause significant air quality impacts in the vicinity of the busiest airports.

The objective of this study is to determine the potential of restricting the use of reverse thrust as an emissions reduction strategy for airports. Instead of using reverse thrust for deceleration during landing, it is proposed that aircraft can use wheel brakes only for stopping. It is also proposed that using an aircraft tow for backing away from a gate greatly reduces NO<sub>x</sub> emissions over power-backing.

In order to evaluate the feasibility of restricting thrust reverse, the factors which influence the use of reverse thrust must be determined and NO<sub>x</sub> emissions from thrust reverse must be quantified. Then, emissions benefits from not using reverse thrust must also be determined by comparing emissions before and after the restriction is implemented. Next, safety considerations must be evaluated to ensure that wheel brakes alone are sufficient for deceleration during landing. Finally, the effect of the proposed emissions reduction strategy on ozone concentrations will be modeled using the Comprehensive Air Quality Model (CAMx).



## **CHAPTER 2. BACKGROUND**

### **2.1 REGULATORY ENVIRONMENT**

Recently, the United States Environmental Protection Agency (EPA) has worked with the Federal Aviation Administration (FAA) and the International Civil Aviation Organization (ICAO) in the development of international aircraft emissions standards. The FAA is responsible for enforcing aircraft emissions standards set by the EPA through certification of aircraft. The EPA has aggressively addressed automobile emissions and aircraft emissions (to a lesser extent) since its formation in 1970.

Table 2-1 shows a chronology of aircraft engine emissions regulation by the EPA. In 1973, emissions standards were implemented which placed limits on smoke emissions for all jet engines and limits on hydrocarbons, carbon monoxide, and oxides of nitrogen for aircraft engines producing more than 29,000 lbs of thrust. At the time, the Pratt and Whitney JT3D and JT8D were the dominant jet engines in commercial aviation. The Pratt and Whitney JT9D, General Electric CF6, and the Rolls Royce RB211 were just entering service and were the only engines which produced more than 29,000 lbs of thrust. For the criteria air pollutants, early emissions standards were specified in pounds of pollutant per 1000 lbs of thrust-hours per landing-takeoff cycle (LTO). These standards were later repealed and not replaced with the ICAO standards until 1993.

**Table 2-1 Chronology of EPA Aircraft Engine Emissions Regulation**

Date	Action	Source
Dec 1972	Aircraft emissions standards first proposed	37 FR 26488
July 1973	Proposed standards adopted, emissions limits established for smoke and for CO, HC, NOx for engines producing greater than 29,000 lbs of thrust	38 FR 19088
Sept 1974	Air Transport Association files a petition for extension of compliance date for JT3D engines	41 FR 54861
Aug 1976	Emissions standards for supersonic aircraft adopted	41 FR 34722
Nov 1979	EPA extends compliance date for JT3D engines	44 FR 64266
Dec 1982	Standards for CO and NOx withdrawn, HC standard relaxed until 1984	47 FR 58462
Jan 1983	JT3D retrofit program suspended	48 FR 2716
Jan 1984	Limits on HC and smoke re-enacted	47 FR 58462
1997	EPA formally adopts ICAO aircraft emissions standards	

In 1977, an ICAO committee known as the Committee on Aircraft Engine Emissions (CAEE) was formed to study air pollution from aircraft. ICAO first adopted aircraft emissions standards in February 1982. Although aircraft engine manufacturers had already achieved these standards, the US EPA did not formally adopt the same standards until 1997 (EPA Nonroad, 1999). Limits on aircraft engine emissions are enacted in Federal Aviation Regulation (FAR) Part 34, “Fuel Venting and Exhaust Emission Requirements for Turbine Engine Powered Airplanes.”

Early ICAO and EPA standards required engine manufacturers to measure gaseous engine emissions at four levels of engine operation:

**Table 2-2 Aircraft Modes of Operation (ICAO, 1993)**

Phase	Power Setting	Default Time-in-Mode (min)
Take-off	100%	0.7
Climbout	85%	2.2
Approach	30%	4.0
Idle	7%	26.0

ICAO also specifies the methodology to be used for computing emissions in the vicinity of airports, using the aircraft engine emissions factors provided by the manufacturers. Emissions

of each pollutant are computed in terms of landing and takeoff cycles (LTOs) by using Equation 2-1.

$$E_i = \sum_j \sum_k [TIM_{jk} * FF_{jk} * EI_{ijk}] * NE_j * LTO_j \quad (2-1)$$

where:

- $E_i$  = Total annual emissions of pollutant  $i$
- $TIM_{jk}$  = time-in-mode for mode  $k$  in minutes for aircraft type  $j$
- $FF_{jk}$  = Fuel flow rate for mode  $k$  in kg/min for each engine used on aircraft type  $j$
- $EI_{ijk}$  = Emission index for pollutant  $i$ , in grams of pollutant per kilogram of fuel consumed during mode  $k$  for aircraft type  $j$
- $NE_j$  = Number of engines used on aircraft type  $j$
- $LTO_j$  = Number of annual landing-takeoff cycles for aircraft type  $j$

ICAO standards also place limits on smoke emitted by aircraft, unburned hydrocarbons, carbon monoxide and oxides of nitrogen. In order for aircraft engines to receive certification, they had to achieve the following standards, which apply to engines generating more than 26.7 kN (6,000 lbs) of thrust:

#### Smoke

The Smoke Number is a “dimensionless term which quantifies the smoke emission level based upon the staining of a filter by the reference mass of an exhaust gas sample.” It is rated on a scale of 0 to 100. The Smoke Number at any thrust setting shall not exceed the level determined by the following:

$$\text{Regulatory Smoke Number} = 83.6 (F_{oo})^{-0.274} \text{ or a value of 50, whichever is less}$$

Gaseous emissions of the following pollutants must not exceed the following during an LTO cycle:

### Hydrocarbons

$$D_p/F_{oo} = 19.6 \text{ g/kN} \quad (2-2)$$

### Carbon Monoxide

$$D_p/F_{oo} = 118 \text{ g/kN} \quad (2-3)$$

### NOx

$$D_p/F_{oo} = 40 + 2\pi_{oo} \text{ g/kN} \quad (2-4)$$

where:

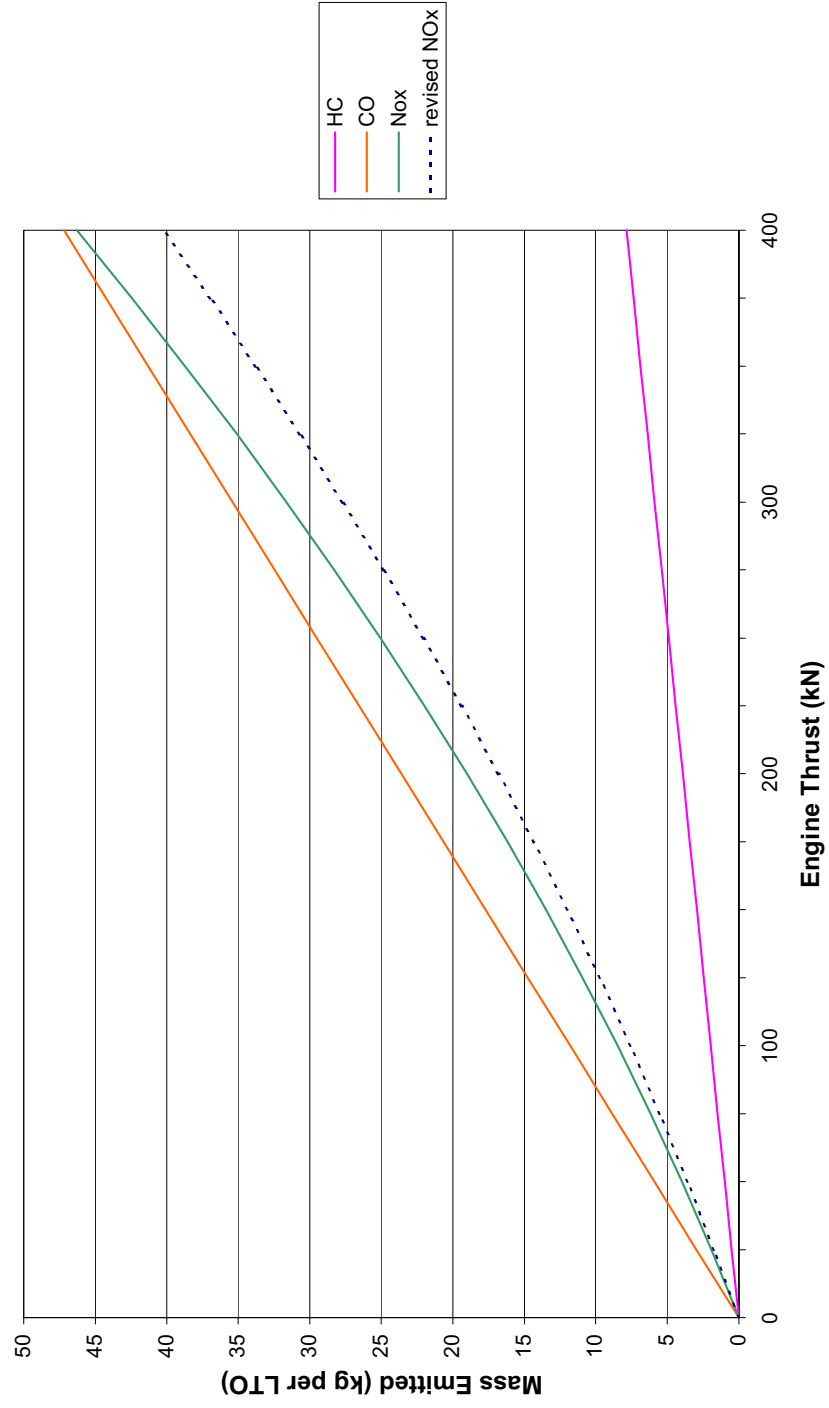
- $D_p$  = mass of the gaseous pollutant emitted in grams per LTO
- $F_{oo}$  = total engine rated thrust output in kN
- $\pi_{oo}$  = engine pressure ratio

All of the ICAO emissions standards are proportional to engine thrust except for the NOx standard, which is based on both engine thrust and engine pressure ratio. Assuming that pressure ratio has a linear relationship with engine thrust, the relationship between the NOx standard and engine thrust becomes quadratic. Figure 2-1 graphically displays the ICAO Engine Emissions Standards for each pollutant. In 1993, the NOx standard was made more stringent, by decreasing the allowable NOx by 20% for engines developed after January 1, 1996 or manufactured before January 1, 2000. The revised NOx standard is shown in Equation 2-5.

$$D_p/F_{oo} = 32 + 1.6\pi_{oo} \text{ g/kN} \quad (2-5)$$

Figure 2-1

### ICAO Engine Emission Standards



## 2.2 COMPUTATION OF AIRPORT EMISSIONS

Current airport emissions inventories include emissions from the airport landside, airside, and stationary sources. Landside emissions result from vehicles used by arriving and departing passengers and employees, which include emissions from passenger cars, shuttles, taxis, and transit. Emissions from the airport airside are produced by aircraft and ground service vehicle operations. Aircraft are assumed to affect urban air quality only when they are inside the mixing layer, which is typically assumed to be under 3,000 feet. As previously discussed, the phases of operation inside the mixing layer include approaching and landing at the airport, taxiing to and from the boarding gate, takeoff and climbing out of the mixing layer. These operations are all part of a landing-takeoff cycle (LTO).

Engine emissions factors have the units of grams of pollutant per kilogram of fuel burned. To compute aircraft emissions, the emissions factor for each mode is multiplied by the amount of fuel burned and by the number of engines. Fuel consumed during each phase is computed by multiplying the fuel burn rate by the duration of operation, or time-in-mode (TIM). Average TIMs for each type of aircraft have been developed by ICAO. Their values are shown in Table 2-3:

**Table 2-3 Time-In-Mode Values (min)**

Mode	Jet	Commuter
Approach	4.0	4.5
Taxi	26.0	26.0
Takeoff	0.7	0.5
Climbout	2.2	2.5

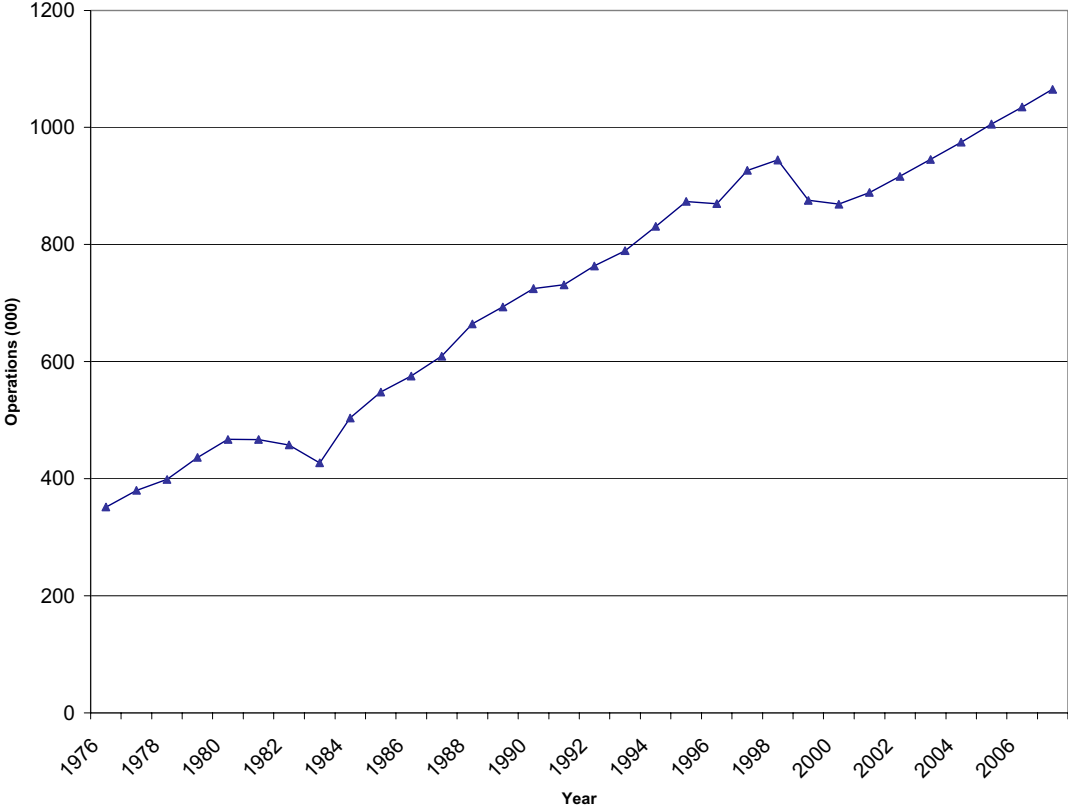
Two software programs are currently used by airports to develop emissions inventories: FAA Aircraft Engine Emissions Database (FAEED) and Emissions and Dispersion Modeling System (EDMS). Both programs develop aircraft emissions inventories according to the ICAO methodology previously discussed. FAEED computes emissions from aircraft only. EDMS computes emissions from both airside and landside sources, including emissions from ground service equipment, aircraft auxiliary power units, and passenger vehicles. EDMS also models the dispersion of pollutants away from the airport.

### **2.3 DFW AIRPORT EMISSIONS IN 2007**

Many metropolitan areas, including Dallas, are seeking reductions in NOx emissions to achieve attainment with the NAAQS. The Dallas region is seeking a 45% reduction in regional NOx emissions, while Houston is seeking a 75% reduction in NOx emissions by the year 2007. With the rapid growth in air travel, increases in NOx emissions from aircraft may offset other reductions achieved on the landside or the airside. In some cases, the relative contribution of NOx emissions from airports will more than double by 2010. Therefore, NOx emissions control strategies for aircraft are urgently needed.

For this study, NOx emissions estimates for DFW Airport in 2007 were developed by using the FAA's traffic growth forecasts and current emissions control strategies. The FAA Terminal Area Forecast forecasts a growth in flights of 21.9% between 1996 and 2007. Figure 2-2 shows historical operations growth at DFW Airport. Aircraft operations are projected to increase from 869,831 in 1996 to 1,065,000 in 2007. It was assumed that aircraft NOx emissions would also increase by a similar amount. For GSE emissions, it was assumed that the all-electric GSE proposal becomes law and that 2007 levels will represent a 90% decrease in GSE NOx emissions from 1996. The state implementation plan (SIP) for the Dallas region specifies an overall 75% NOx reduction from point sources and a 50% reduction in NOx from motor vehicles. It was assumed that these reductions would occur at the airport as well. Table 2-4 shows DFW airport emissions for 1996 and 2007.

**Figure 2-2 Historical Operations Growth at DFW Airport**



source: FAA, 2000

**Table 2-4 NOx Emissions Forecasts for DFW International Airport**

1996		2007	
Source	tons/yr	growth method	tons/yr
Aircraft	5027	TAF	6128
GSE	5504	90% reduction	550
Point	66	75% reduction	16.5
Landside	1136	50% reduction	568
Aviation-Related Total	11733		7262
Region Total	186854		103054
airport %	6.29%		7.05%

These figures assumed that the 100% GSE electrification requirement was implemented. Since the law was subsequently overturned, the airport’s contribution of regional NOx will likely be substantially higher.

Table 2-5 shows the breakdown of emissions by phase of operation for an MD-80 aircraft engine. The majority of aircraft emissions are off-airport and elevated. Not including emissions from reverse thrust, approximately 63% of the NOx emissions are generated off-airport, during approach and climbout.

**Table 2-5 Emissions by Mode for JT8D-217 Engine, per LTO cycle**

phase	power setting	time (sec)	fuel flow (kg/s)	fuel burned (kg)	NOx (g)	total (g)	
Takeoff	100%	0.7	1.32	55.4	1424.8	1484.7	23.8%
Climbout	85%	2.2	1.078	142.3	2931.3	3167.5	49.0%
Approach	30%	4	0.3833	92.0	837.1	1367.9	14.0%
Idle	7%	26	0.1372	214.0	791.9	4130.8	13.2%
Total					5985.2	10150.9	100.0%

source: ICAO (1995)

## 2.4 THRUST REVERSERS

Restricting the use of reverse thrust is a potential emissions reduction strategy that is at present not widely practiced. Reverse thrust is a high engine power operation which generates NO<sub>x</sub> that is not currently accounted for. Almost all modern commercial jet aircraft are equipped with thrust reversers, which reverse or deflect the direction of engine thrust. Thrust reverse mechanisms introduce an aerodynamic structure behind an engine which deflects the power produced by the engine forward. Thrust reversers are primarily used during landing, along with wheel brakes to slow an aircraft.

There are two types of engine thrust reversers: cascade and clamshell reversers. Cascade reversers are found on aircraft engines with large fans and high bypass ratios. When a cascade reverser is deployed, part of the engine nacelle slides backwards and a blocker door inside the engine deflects the airflow outward through a series of cascade vanes, which then direct the airflow forward. With a cascade reverser, only the airflow from the engine fan is reversed. The heated airflow from the turbine is still directed backwards. With cascade reversers, net reverse thrust produced is typically 15-20% of the normal forward thrust (Rothstein, 2000). Cascade reversers are commonly found on newer aircraft, including B737s, B757s, B767s, and all Airbus aircraft.

Clamshell reversers are found on primarily on older aircraft with smaller engines and lower bypass ratios. Two large blocker doors are pivoted behind the engine which direct the entire engine flow forward. They are primarily found on MD-80s, DC-9s and older model B737s. With clamshell reverses, net reverse thrust produced is 30-40% of forward thrust (Rothstein, 2000).

Pilots use a combination of reverse thrust and wheel brakes to decelerate during landing. Reverse thrust is used after the nose gear of the airplane touches down until the aircraft slows to 40-50 knots, then wheel brakes are used to slow the airplane further. Engine manufacturers recommend using reverse thrust at speeds above 45 knots to prevent exhaust gas and debris ingestion (Rothstein, 2000). Reverse thrust is preferred by pilots on slick runways as a braking aid, when brakes are less effective.

The amount of reverse thrust used depends heavily on the runway condition, length, exit location, and exit configuration. On short runways, reverse thrust is used more intensely than on long runways. Because of the short runway, the pilot has little room for error and must slow the

plane quickly. On modern runways with high speed turnoffs, the runway exits are angled, so the plane can exit the runway at a higher speed. On runways with right-angled exits, the aircraft has to slow almost to a stop before exiting. In both cases, the pilot may decelerate more or less heavily so he can take the most convenient exit.

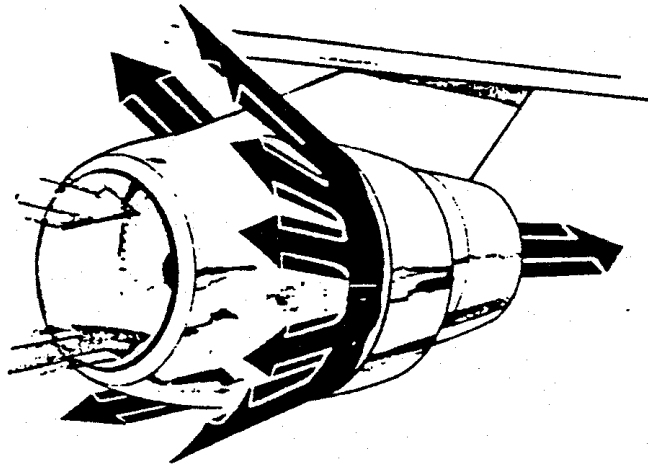
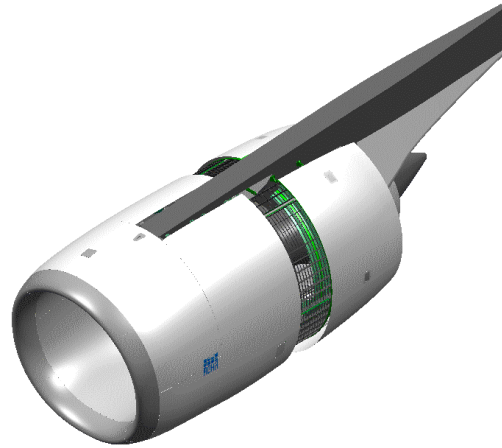
Thrust reversers are occasionally used to back aircraft away from boarding bridges. This is known as “power-backing”. There are a lot of characteristics which determine whether or not an aircraft will be power-backed. These include location and type of engines, layout of terminal area, ample room, proximity of surrounding aircraft, and availability of ramp personnel and aircraft tows (Vance, 2000).

At DFW International Airport, American Airlines power-backs its aircraft whenever possible. American operates 64 gates at DFW and power-backs are permitted at 40 of the 64 gates. The only aircraft which are capable of being power-backed are MD-80s, F-100s and Boeing 727s, which represent 85% of American’s traffic (Hotard, 2000). American operates 530 daily flights at DFW. This indicates that roughly 300 aircraft are “power-backed” daily at DFW Airport.

Restrictions on reverse thrust usage are very common at European airports. Munich, Zurich, Copenhagen, and Cologne-Bonn do not allow aircraft to use more than idle reverse thrust. London Heathrow, Oslo, and Paris-Orly have restrictions on reverse thrust usage at night only (Boeing, 2000). Although the primary motivation for these restrictions is noise, there are presumably fuel savings and emissions benefits as well.

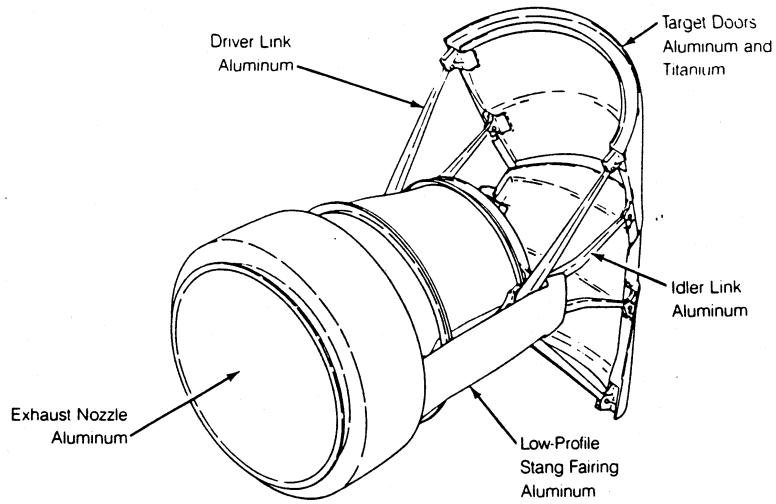
American Airlines is currently the only carrier which practices widescale power-backing. American prefers to power-back whenever possible and does so unless safety is compromised (Hotard, 2000). In Texas, Austin, DFW, and El Paso are the only airports where power-backing is practiced. At other airports, power-backing is either prohibited by the airport administration or by the ramp configuration. Power-backing at Chicago O’Hare and LAX is not practiced because of the lack of space between terminal buildings. In Atlanta, where terminal buildings are spaced 1,000 feet apart, power-backing is practiced by American only, as Delta does not power-back. Figures 2-3 and 2-4 show the two different types of thrust reversers.

**Figure 2-3 Examples of Cascade Thrust Reversers**



source: BF Goodrich Aerospace

**Figure 2-4 Example of Clamshell Thrust Reverser**



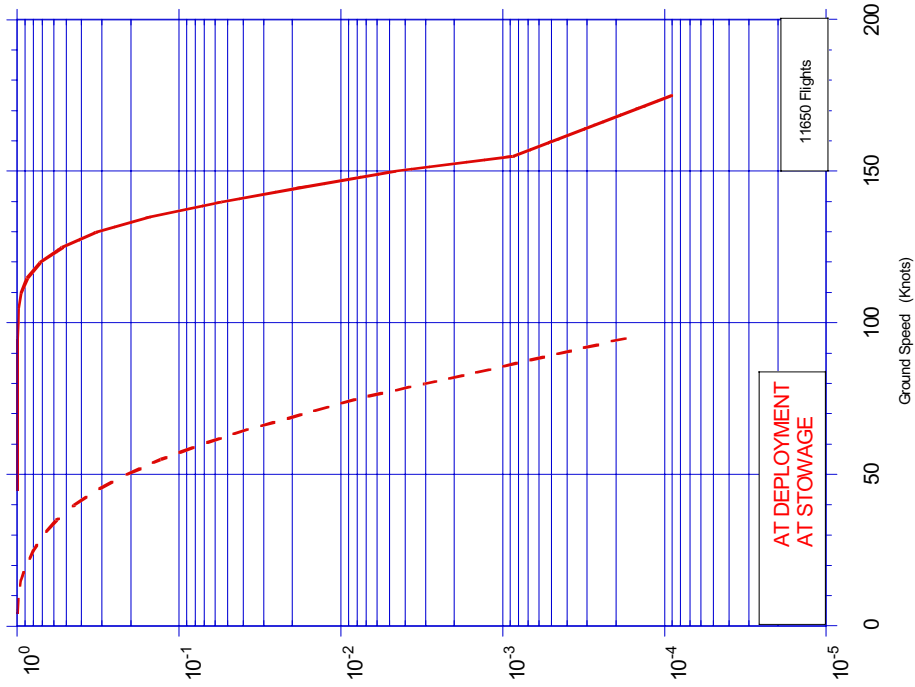
source: BF Goodrich Aerospace

## 2.5 DATA ON THRUST REVERSER USAGE

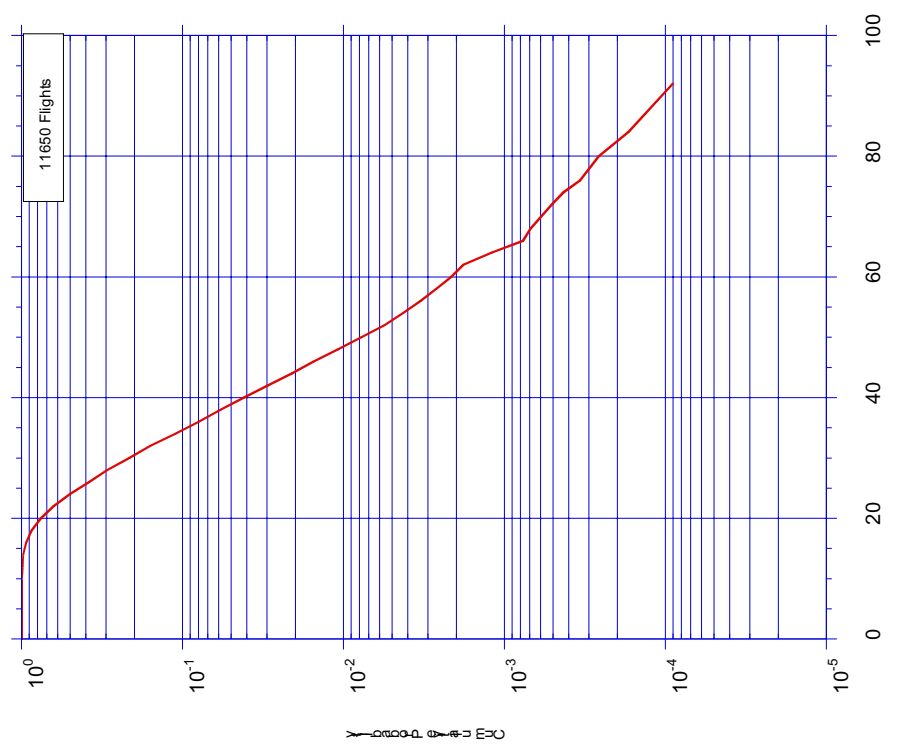
“Statistical Loads Data for Boeing B737-400 Aircraft in Commercial Aircraft Operations”, FAA Report AR/98-28 and “Statistical Loads Data for MD 82/83 Aircraft in Commercial Aircraft Operations, FAA Report AR/98-65 were published in 1998 and 1999. These reports provide numerous statistical summaries of operating characteristics collected onboard Boeing 737-400 and MD-80 aircraft. The data include statistical information on acceleration, speed, altitude, flight duration and distance, speed brake/spoiler cycles, and thrust reverser usage; 19,105 flight hours were recorded on B737s and 7120 flight hours on MD-80s. The data was collected through the FAA Airborne Data Monitoring Systems Research Program and analyzed by the University of Dayton Research Institute (UDRI).

The most relevant statistics provided by this report are the duration of thrust reverser deployment, speeds during thrust reverser usage, and engine power settings during thrust reverser deployment. Cumulative probability distributions for these statistics are shown in Figures 2-5 through 2-8, courtesy of UDRI. These charts show that median time of thrust reverse usage during landing is slightly more than 20 seconds for the B737-400 and approximately 10 seconds for an MD-80. The median speed for thrust reverser deployment was between approximately 120 knots and 40 knots for the B737, and the median maximum engine power setting ( $N_1$ ) during thrust reverse was 80%.

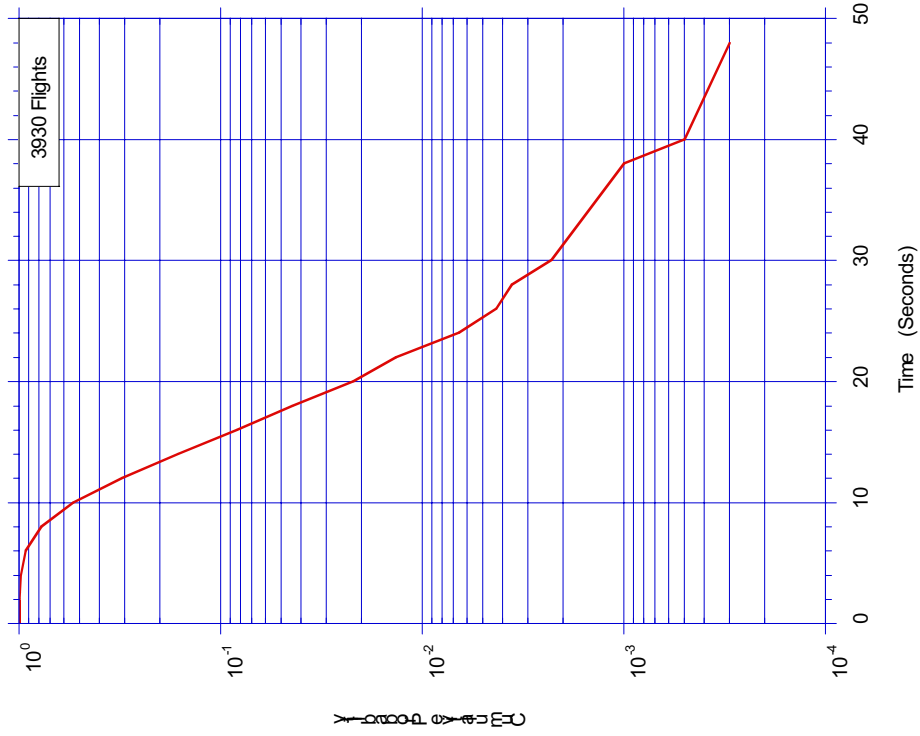
Data means were not computed by UDRI. However the data used to generate the cdfs were provided. Figures 2-9 and 2-10 show probability density functions of Figures 2-5 and 2-6. Using this data, the mean thrust reverser usage was estimated to be 26.3 seconds for the B737-400 and 11.7 seconds for the MD-80.



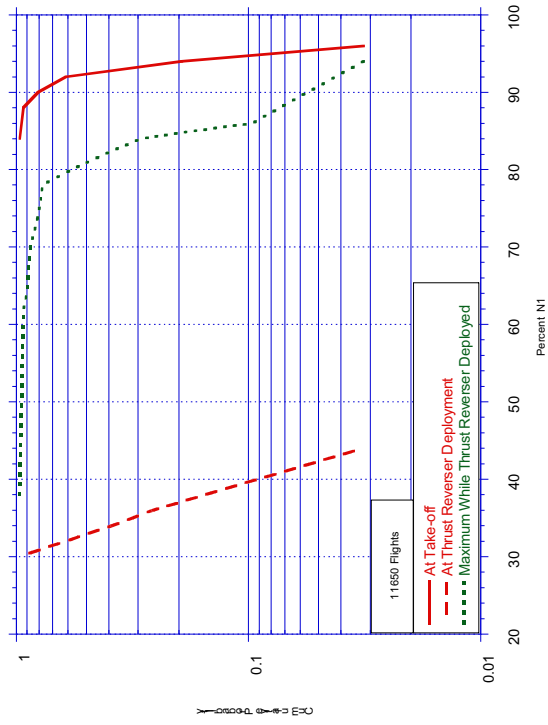
**Figure 2-5 Cumulative Probability of Time With Thrust Reversers Deployed for B737-400**



**Figure 2-6 Cumulative Probability of Speed at Thrust Reverser Deployment and Stowage for B737-400**



**Figure 2-8 Cumulative Probability of Time With Thrust Reversers Deployed for MD-80**



**Figure 2-7 Cumulative Probability of Percent of  $N_1$  For B737-400**

**Figure 2-9**  
**Thrust Reverser Deployment Time B737-400**

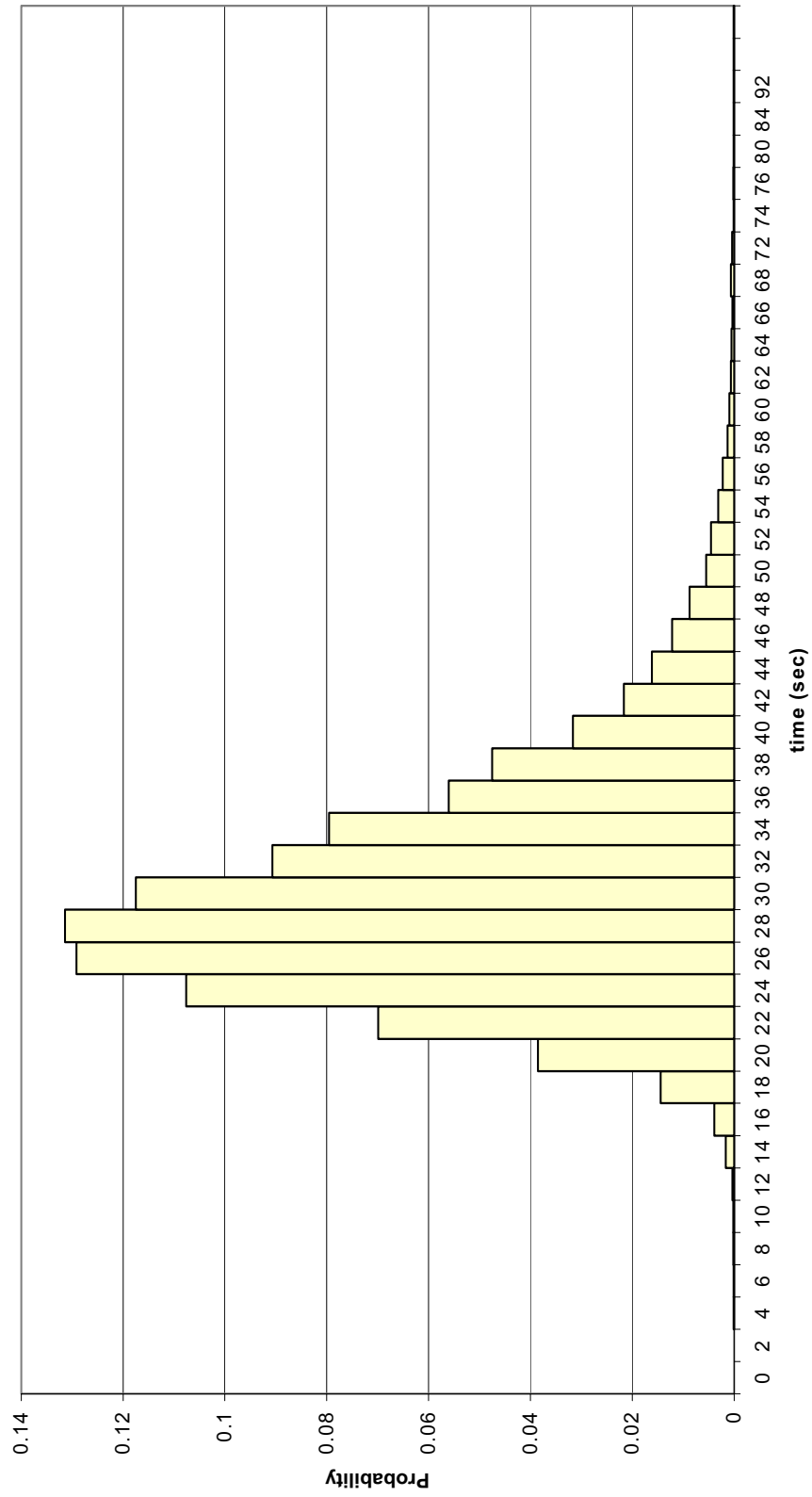
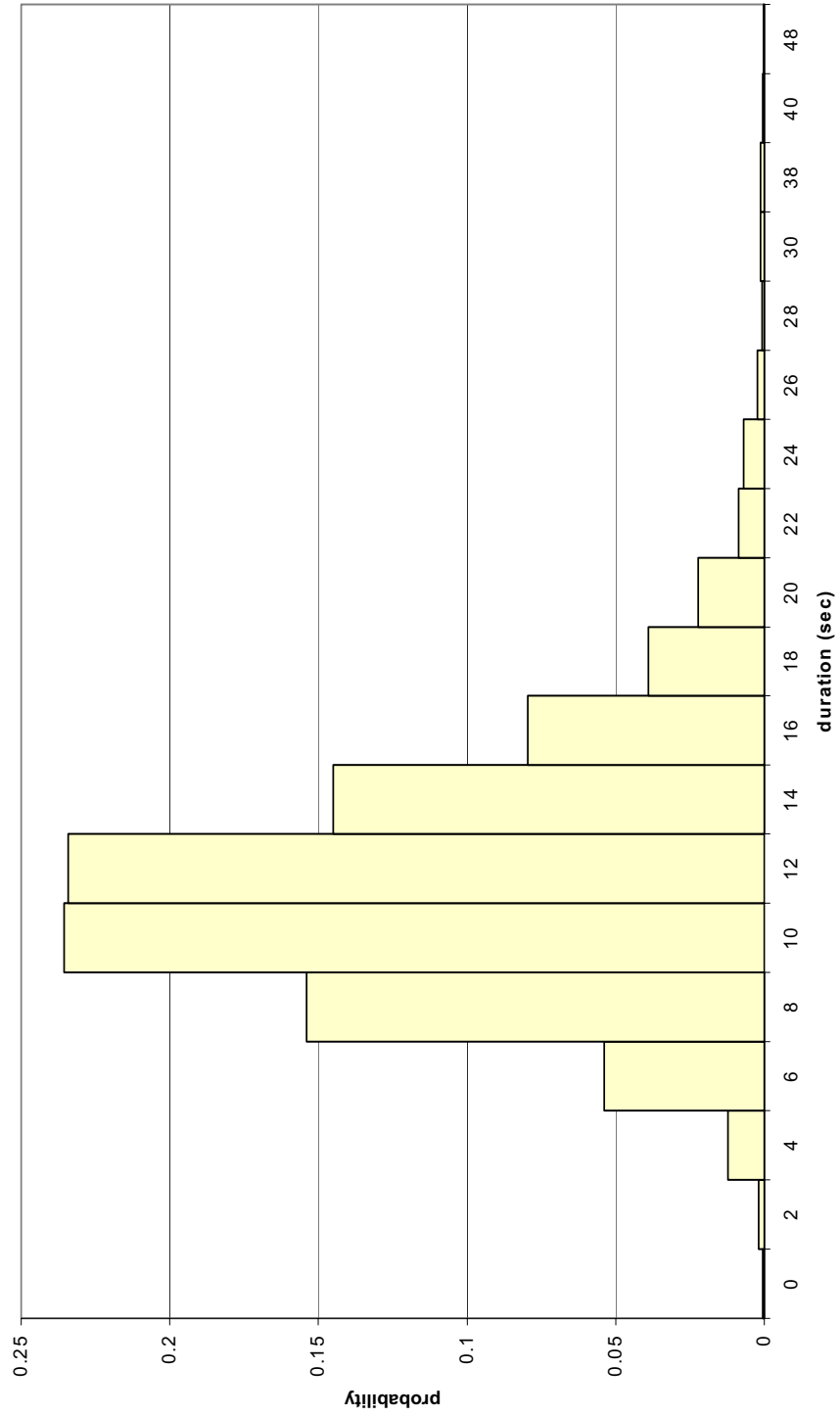


Figure 2-10

Duration of TR Deployment - MD80



## 2.6 MODIFICATION OF EMISSIONS FACTORS

This report also suggests that aircraft emissions for any power setting, at any altitude and temperature can be approximated if the combustor inlet temperature  $T_3$  and pressure  $P_3$  are known.  $T_3$  and  $P_3$  can be obtained either from an engine simulation or engine test data. A correction factor is applied to the existing ICAO emissions factors,  $REI$ .

$$W_{ff} = \frac{W_f}{\theta_{amb}^{1.5}} \quad (2-6)$$

$$EI(HC,CO) = REI(HC,CO) / \delta_{amb}^4 \quad (2-7)$$

$$EI(NO_x) = REI(NO_x) * \theta_{amb} * e^H \quad (2-8)$$

where:

$W_f$  = fuel flow

$W_{ff}$  = fuel flow factor

$\delta, \theta$  = temperature and pressure ratios

$e^H$  = humidity correction factor

$$\theta_{amb} = \frac{T_{amb}}{288.16} \quad (2-9)$$

$$\delta_{amb} = \frac{P_{amb}}{101.32} \quad (2-10)$$

Using this formulation with the temperature and pressure data from the engine simulation, a nearly linear relationship between the emissions indices is shown for each pollutant. These relationships are shown in the report and can likely be validated with additional emissions testing.



## **CHAPTER 3. LITERATURE REVIEW**

Literature searches were conducted using keyword searches with the Transportation Research Information Services (TRIS), Engineering Village, the NASA Library, and Cambridge Scientific Abstracts. Previously, most transportation and air quality research has focused on reducing automobile emissions. Therefore, a limited of refereed publications were found in the field of airports and air quality.

The literature review is divided into five sections. The first section discusses compilation of aircraft emissions and development of airport emissions inventories. The second section discusses literature on air quality regulation and policy and how it pertains to aviation. The third section provides information on emissions reduction strategies for airports. The fourth section provides pertinent information on previous studies involving thrust reversers and aircraft braking. The final section discusses previous research on similar sources of concentrated NO<sub>x</sub> emissions.

### **3.1 AIRPORT/AIRCRAFT EMISSIONS INVENTORIES**

In Wayson and Bowlby (1989), important issues in developing airport emissions inventories are presented. Six potential problem areas discussed. With aircraft, one complication is that a single aircraft type may be equipped with several different engine versions. For example the DC-9 can be powered by several different engines, depending on the aircraft model (DC-9-10, DC-9-30, etc). Adequate times-in-mode data should also be determined. Usage times need to be collected on GSE, prior to modeling. Emissions from stationary sources must also be computed. Finally, emissions from motor vehicles used for airport-related trips should be assessed from beginning of the journey to the airport, instead of the portion on airport property only. Wayson and Bowlby (1989) also discuss the use of EDMS and recommend the use of a spreadsheet to enable easy revisions and recalculation of the aircraft component of emissions. Using the spreadsheet method, different scenarios for airport emissions inventories can be computed quickly, while errors in calculations are avoided (Bowlby and Wayson, 1990).

URS Greiner (1998) developed an emissions inventory for DFW Airport. Emissions estimates of CO, NO<sub>x</sub>, and VOCs are presented for years 1996, 1999, 2002, and 2015 from

aircraft, ground service equipment, vehicles, refueling, and stationary sources. DFW's emissions inventory from 1996 is shown in Table 3-1. Although EDMS can model passenger vehicle and GSE emissions, for this study, it was used for the aircraft modeling only. MOBILE5 and the EPA Non-Road database were used to model the other emission sources.

**Table 3-1 1996 DFW Airport Emissions Inventory**

Source Category	VOC (tons/yr)	NOx (tons/yr)	CO (tons/yr)
Aircraft	1636	5027	5,051
GSE	826	5504	6694
Stationary	4	66	7
Fueling	12.5	---	---
Airport Subtotal (tons/yr)	2479	10597	11752
Motor Vehicles	554	1136	4832
TOTAL (tons/yr)	3033	11733	16584

Future aircraft emissions were forecasted by using air traffic and fleet projections for years 1999, 2002, and 2015. Vehicle emissions were forecasted by using the future vehicle emissions factors and fleet turnover. Stationary source emissions are forecasted by growth in terminal building size and aircraft operations.

URS Greiner (1998) computed DFW Airport's GSE emissions by using a ratio of GSE emissions to air carrier operations found at other Texas airports in non-attainment areas. GSE emissions at El Paso International (ELP), Houston Intercontinental (IAH), and Houston Hobby Airports (HOU) were referenced, where approximately 8.5 tons per year of NOx from GSE are generated per thousand air carrier operations. Due to the nature of the DFW Airport's terminal layout and hub operation, emissions from GSE are thought to follow a different pattern than at ELP, IAH, or HOU and it is likely that Greiner's estimate of GSE emissions for DFW is overestimated.

EPA Report 420-R-99-013 (1999) focused on emissions from commercial jet aircraft for ten non-attainment metropolitan areas. Aircraft emissions were computed using 1990 activity levels and forecasted out to 2010. In 1990, the aircraft component of the regional mobile NOx emissions ranged from 0.4% to 2.3%. In 2010, the aircraft component of NOx was estimated to increase for all cities, ranging from 1.8% up to 8.1%. Between 1970 and 1995, hydrocarbon and NOx emissions from aircraft grew by 53%, despite implementation of emissions standards for

aircraft engines. Noise regulations and more fuel efficient aircraft engines have reduced hydrocarbon emissions; however, the report finds controlling NOx emissions is a much greater challenge.

### 3.2 AIR QUALITY REGULATION AND POLICY

TNRCC (2000) is the State Implementation Plan for the Dallas/Ft. Worth Non-Attainment region. It discussed the evolution of air quality problems and potential solutions for the Dallas/Ft. Worth area. In order for attainment to be achieved in 2007, the air quality modeling showed that a 45% reduction in regional NOx is necessary (TNRCC, 2000). Also included in the Dallas plan was a proposal to require 100% electrification of airport ground service equipment by 2003. This proposal, which was challenged by the Air Transport Association, will be discussed further in Chapter 8. Some of the other proposed emissions reduction measures by category and amount are shown in Table 3-2.

**Table 3-2 Proposed Emissions Reduction Measures for Dallas Region**

<b>Category/Measure</b>	<b>Estimated NOx reduction in 2007 (tpd)</b>
<b>Federal on-road measures</b> <ul style="list-style-type: none"> <li>• Phase II reformulated gasoline</li> <li>• Tier II vehicle emissions standards</li> <li>• Low-emitting vehicle program</li> </ul>	93
<b>Federal off-road measures</b> <ul style="list-style-type: none"> <li>• Lawn and garden equipment</li> <li>• Locomotives</li> <li>• Spark ignition standards for vehicles and equipment</li> </ul>	48
<b>TNRCC issued rules</b> <ul style="list-style-type: none"> <li>• Major point source NOx reduction in 4 counties</li> <li>• Airport GSE electrification</li> <li>• Delayed operation of construction equipment</li> </ul>	129 9.54 2.5
<b>DFW Local Initiatives</b> <ul style="list-style-type: none"> <li>• Speed limit reduction in 9 counties</li> <li>• Transportation control measures in 4 counties</li> </ul>	5.42 4.73

### 3.3 EMISSIONS REDUCTION STRATEGIES FOR AIRPORTS

Most of the previous research in airport emissions reduction has focused ground transportation and airport GSE. Very reduction strategies have been proposed for aircraft. In Higgins (1994), a method of estimating the number of airport ground access trips and related emissions based on passenger enplanements was proposed. The potential of several employee and passenger VMT reduction measures was also investigated. Higgins (1994) also found that employee vehicle trips may be responsible for as much as 40% of all daily airport trips and 20% of VMT associated with the airport. It was concluded that parking fees hold the most promise for reducing employee trips and that charging access tolls for all vehicles, including buses and shuttles, would reduce total airport trips. Fabian (1993) also focuses on VMT reduction associated with airports, noting that few “airfront districts” have been comprehensively planned. Airport people movers systems at major airports are compared, while cost-benefit analyses are performed.

Draper, Pernigotti, et al (1997) outlined the air quality assessment process for airports and air force bases and discuss several potential airside emissions reduction measures, including single engine taxi, derate takeoff power, and reducing the use of reverse thrust. These strategies are conceptually discussed, however no attempt is made to quantify the potential emissions reduction.

Yamartino and Spitzak (1994) suggested that airport emissions reduction measures proposed for the Los Angeles basin would be less effective in practice than initially forecasted. The shortcomings of the ICAO aircraft emissions computation methodology are discussed. It was noted that aircraft weight does not impact emissions computations and that takeoff power settings are rarely at full power. Yamartino and Spitzak (1994) also mentioned that noise and engine wear considerations have already encouraged airlines to reduce takeoff and climbout power settings. It is also mentioned that further reductions in aircraft NO<sub>x</sub> are unlikely to be achieved by modifying takeoff and climbout procedures.

In EPA 420-R-99-007 (1999), the benefits of alternative fuel GSE were evaluated. Emissions are compared among diesel, gasoline, compressed natural gas (CNG), liquified propane gas (LPG), and electric powered versions of a multitude of GSE. LPG and CNG were estimated to reduce GSE hydrocarbon emissions by 50-75% and NO<sub>x</sub> emissions by 20-25%, when compared with gasoline-powered GSE. When compared with diesel powered GSE, CNG

and LPG were estimated to increase hydrocarbons significantly, while decreasing NO<sub>x</sub> by 75-80%. Electric GSE were found to reduce both hydrocarbon and NO<sub>x</sub> emissions by more than 90%. The major drawback of electric GSE was found to be the purchase price.

### **3.4 THRUST REVERSERS AND BRAKING**

In Yetter (1995), airlines were surveyed regarding their thrust reverser usage. Thrust reversers were shown to have a significant impact on engine nacelle design, cruise performance, aircraft weight, and maintenance costs. Because of the added weight, thrust reversers can increase specific fuel consumption by 1.0%. Thrust reversers are not used during aircraft certification and are not required by FAA regulations. They are most useful on contaminated runways, when wheel braking effectiveness is greatly diminished.

Most carriers responded that thrust reverse is needed to provide additional stopping force in adverse weather conditions and most deploy them during every landing. The airlines felt that thrust reversers add a margin of safety for aircraft operations. Most airlines cited that using thrust reverse minimizes the amount of wheel braking required and that during landing, the engines are operated at 70-80% power. When asked about power-backing, a small number of airlines reported that power backs are used to minimize ground handling equipment and ground crew personnel requirements. Power backs are usually limited to aircraft with rear-mounted engines.

Yetter (1995) also noted that all Boeing 767 thrust reversers were temporarily disabled after a crash resulted from a reverser deploying during flight. The FAA implemented the restriction while the cause of the deployment was being investigated. During this time, takeoff weights were restricted for airlines flying the B767.

Yager, Vogler, and Baldasare (1990) presented braking performance information for Boeing B727-100 and B737-100 aircraft under a variety of runway conditions. Tests were performed on dry, wet, snow and ice covered runways using varying levels of wheel brakes and engine thrust reversers. On dry runways, the tire skidding coefficient of friction was found to be near 0.5. On wet runways, the friction coefficient ranged between 0.1 and 0.5, depending on the amount of water present on the runway surface. On surfaces covered with loose snow, friction coefficients varied directly with speed and ranged from 0.1 at 10 knots to 0.2 at 90 knots. On glare ice, friction coefficients were found to be 0.1 at 10 knots and nearly zero at 90 knots. These results support the need that thrust reversers are greatly needed when runways are wet or icy.

### **3.5 OTHER CONCENTRATED SOURCES OF NO<sub>x</sub> EMISSIONS**

Because of the significant concentration of NO<sub>x</sub> emissions, a major airport's effect on air quality may be similar to a power plant's. In Luria et al (1999), formation of ozone associated with power plant plumes was investigated in central Tennessee. Increased ozone levels were found along the edges of the plume, while decreased ozone levels were found in the center of the plume near the power plant. Ozone production was delayed until the plume was diluted, a significant distance downwind. Elevated levels of nitrogen dioxide and nitrates were also found inside the plume.

Gillani et al (1998) finds that approximately 33% of U.S. anthropogenic NO<sub>x</sub> emissions in 1993 were produced by electricity generation. Production of ozone in power plant plumes near Nashville were also studied. Peak yields of ozone from the plumes were found to occur within 30-40 km of smaller power plants and within 100 km for the larger plants. Gillani et al also determined that 3.1 molecules of ozone per molecule of NO<sub>x</sub> emitted may be formed by power plants and that an increase of 50 ppb of ozone over Nashville may be attributed to nearby power plants.

## CHAPTER 4. EXPERIMENTAL DESIGN AND DATA COLLECTION

### 4.1 BACKGROUND

The factors which influence reverse thrust usage during landing are thought to be the similar to the factors which influence aircraft landing distance. These include temperature, wind, runway gradient, altitude, and runway surface condition (Horonjeff, 1992). Thrust reversers are typically used to provide deceleration immediately after touchdown and, as previously discussed, are recommended by manufacturers to be used at speeds above 60 knots, to prevent debris ingestion into the engines.

**Table 4-1 Commercial Jet Aircraft in Service at ABIA during November 2000**

Aircraft	Airlines Operating	# of engines/type	Thrust per engine (lbs)	Reverser Type
B737-300/NG	Southwest Continental America West Delta United	2-CFM-56	22,000	Cascade
B737-200	Southwest Delta	2-Pratt/Whitney JT8D-9/15	16,000	Clamshell
B757	American	2-Rolls Royce RB211-535	40,000	Cascade
B727-200	Delta United	3-Pratt/Whitney JT8D-15/17	17,000	Cascade
DC-9	Northwest TWA	2- Pratt/Whitney JT8D-9	14,000	Clamshell
MD-80	American Continental Delta TWA	2-Pratt/Whitney JT8D-219	20,000	Clamshell

## 4.2 PRELIMINARY ANALYSIS

A preliminary analysis of reverse thrust usage was performed at ABIA during Summer 2000 to determine the basic characteristics influencing reverse thrust usage. The airport is served by 2 runways and 8 passenger airlines who operate 6 basic types of aircraft. Data was collected at various sites outside the perimeter fence, including the golf course along the east runway, the former Air Force propulsion building near the east runway, a cemetery at the northern end of the west runway, airline cargo buildings along the west parallel taxiway, and inside the passenger terminal.

For the preliminary analysis, 31 landing reverse thrust operations were timed. During landing, reverse thrust was used for an average of 16.8 seconds, with a standard deviation of 3.7 seconds. Most of the general aviation traffic uses the east runway, as it is closer to the fixed base operators. During south flow, most planes have a shorter distance to taxi when they land on the west runway. Because of the airport's runway layout, the most commonly used exits for the west runway are near midfield, close to the cross taxiways. For these reasons, most of the planes sampled landed on the west runway. The average duration did not differ much by runway. For this analysis, aircraft were sampled during all time periods of the day. No significant difference was found for reverse thrust usage according to time of day.

Boeing 737s are the aircraft most frequently flown to ABIA, followed by MD-80s. Boeing 727 aircraft appeared to have the longest duration of usage at 20 seconds, while newer Boeing 737s appeared to have the shortest at 16.4 seconds. Although aircraft deceleration may be affected by a wet runway, aircraft emissions during inclement weather are assumed to have little effect on local air quality, as ozone precursors are "washed out" by rainfall. For this reason, all samples were taken during good weather, while the runways were dry. Preliminary results are shown in the Tables 4-2 through 4-4.

**Table 4-2 Average Usage by Aircraft Type**

Aircraft Type	Number of Landings	Average Duration (sec)
B727-200	2	20.0
B737-200	3	20.3
B737-300	15	16.4
DC-9	2	19.0
MD-80	9	17.0

**Table 4-3 Average Usage by Runway**

Runway	Number of Landings	Average Duration (sec)
West (17R/35L)	19	16.75
East (17L/35R)	12	16.88

**Table 4-4 Average Usage by Airline**

Airline	Number of Landings	Average Duration
American	4	16.3
Continental	5	16.5
Delta	4	20.3
Northwest	1	18.0
Southwest	13	18.4
TWA	1	13.0
United	1	19.0

As expected, thrust reverse usage appears to vary by aircraft type and airline. Little variation is noticed between runways. Because of their design, clamshell thrust reversers are more efficient than cascade reversers. Clamshell reversers divert more engine thrust forward, causing the aircraft to decelerate faster. Therefore, aircraft with clamshell thrust reversers are assumed to use thrust reverse for a shorter duration than aircraft with cascade reversers. It is also assumed that differences in thrust reverse usage will be noticed among airlines, reflecting differences in pilot training and airline policy.

#### **4.3 EXPERIMENT DESIGN FOR LANDING AIRCRAFT**

Based on the results of the preliminary analysis, a two-factor factorial design was used for the collection of data on reverse thrust usage during landing. The null hypothesis can be stated as follows:

*H<sub>0</sub>: There is no significant difference in reverse thrust usage among aircraft type and airline*

The response variable was reverse thrust duration and the set of factors included aircraft type and airline, both fixed. Factors aircraft type and airline will have six and eight levels, respectively. Observations are coded as  $y_{ijn}$  where  $i$  is the airline,  $j$  is the aircraft, and  $n$  is the replication. The general layout for the experiment will be similar to Table 4-5.

**Table 4-5 General Arrangement for Two-Factor Factorial Design**

	American	Continental	...	b
B737-300/NG	$y_{111}, y_{112}$ $y_{113}, y_{114}$	$y_{121}, y_{122},$ $y_{123}, y_{124}$		$y_{1b1}, y_{1b2},$ $y_{1b3}, y_{1b4}$
737-200	$y_{211}, y_{212},$ $y_{213}, y_{214}$	$y_{221}, y_{222}$ $y_{223}, y_{224}$		
B757	$y_{311}, y_{312},$ $y_{313}, y_{314}$			
....				
a	$y_{a11}, y_{a12}$ $y_{a13}, y_{a14}$			$y_{ab1}, y_{ab2},$ $y_{ab3}, y_{ab4}$

Operating characteristic curves are used to determine the number of replications needed for an experiment. An operating characteristic curve is a plot of the type II error probability  $\beta$  for a particular sample size that shows the range in which the null hypothesis is false (Montgomery, 1997). Using the numerator and denominator degrees of freedom and a parameter  $\phi$ , which is computed using a trial number of replications  $n$  and the sample variance, the number of replications needed to achieve an acceptable  $\beta$  can be iteratively determined.

The parameter  $\phi$  is defined in equation 4-1:

$$\phi^2 = \frac{nbD^2}{2a\sigma^2} \quad (4-1)$$

where:

- n = number of replications
- D = minimum difference between any two treatment means
- a = number of levels of treatment A
- b = number of levels of treatment B
- $\sigma$  = standard deviation of sample

For this experiment, it was decided that the null hypothesis should be rejected if the difference in usage  $D$  between aircraft was as much as 2.0 seconds. Equation 4-1 then simplifies to equation 4-2:

$$\phi^2 = 0.196n \quad (4-2)$$

Next, we find the number of replications needed to achieve an acceptable level of  $\beta$ .

**Table 4-6 Iterations to Achieve an Acceptable  $\beta$**

n	$\phi^2$	$\phi$	$v_1$ numerator df	$v_2$ error df	$\beta$
2	0.392	0.626	7	48	-
3	0.588	0.767	7	96	-
4	0.784	0.885	7	144	-
...	0.196n	$\sqrt{0.196n}$	a-1	ab(n-1)	from chart
6	1.18	1.08	7	240	0.4
12	2.352	1.534	7	528	0.15
13	2.548	1.596	7	576	0.05

For this experiment, we find that 13 replications are needed per airline/aircraft combination to achieve  $\beta=0.05$ . This translates into  $abn=624$  total observations.

Because of their relatively low frequencies, late arrival times, and variable schedules, cargo airlines were omitted from the experimental design. Federal Express operates a maximum of six flights per day, four of which are turboprop aircraft. After collecting the data, analysis of variance was performed. The variance was isolated among both factors and the interactions between each of the factors will be evaluated.

#### 4.4 SAMPLE DESIGN FOR POWERBACKS

American Airlines is the only carrier who practices power-backing at ABIA. When leaving a gate, aircraft are power-backed until there is enough room to safely taxi. The duration of power-backing is largely controlled by the pilot himself and the instructions given to him by the ground crew, who walk backwards with the airplane.

Since American Airlines' MD80s are the only aircraft which are power-backed at ABIA, a simple random sample (SRS) of thrust reverser usage was selected as the experimental design.

From the preliminary analysis, reverse thrust during power-backing was used for approximately 45.3 seconds during power backing, with a standard deviation of 5.9 seconds. When estimating the sample size, an acceptable margin of error  $e$  must first be determined. A common value for  $e$  is  $\pm 3\%$ , which translates into a range of  $\pm 1.35$  seconds. Sample size can be found by equating  $e$  to the size of the confidence interval as shown in Equation 4-3 (Lohr, 1999).

$$e = z_{\alpha/2} \sqrt{\left(1 - \frac{n}{N}\right) \frac{S}{\sqrt{n}}} \quad (4-3)$$

Solving for  $n$ , we get

$$n = \frac{z_{\alpha/2}^2 S^2}{e^2 + \frac{z_{\alpha/2}^2 S^2}{N}} = \frac{n_0}{1 + \frac{n_0}{N}} \quad (4-4)$$

$$\text{where } n_0 = \frac{z_{\alpha/2}^2 S^2}{e^2} \quad (4-5)$$

Using the standard deviation  $S$  from the preliminary sample of 5.9 seconds,  $e = 1.35$  seconds,  $z_{\alpha/2} = 1.96$ , we get  $n_0 \approx 74$  aircraft. The value  $n$  represents the sample size needed if the population is finite. It is computed by applying a finite population correction factor to  $n_0$ . The value  $n_0$  is the sample size for a simple random sample with replacement (SRSWR). This estimate of sample size is adequate, as the population over time of American MD-80s at ABIA is assumed to be infinite.

After sample sizes were determined, data collection was commenced. Sections 4-5 through 4-9 discuss the issues and challenges in developing the data collection stations.

#### 4.5 SELECTING A DATA COLLECTION LOCATION

Ideally, the control tower is the best place for data collection. It provides the best view of the airfield and is the best place for data collection efficiency. At airports with multiple runways, all aircraft activity can be sampled from the control tower. However, there are FAA security policies about granting non-employees access to the tower and, therefore, sampling from the tower was not possible. Sampling on the airport grounds near a runway provides the best

precision for reverse thrust duration measurement. Since engine noise is directly related with engine power, it is easier to record when high power settings of reverse thrust are being used. When thrust reversers are deployed, depending on the engine type, it takes approximately 1-2 seconds for the engines to “spool-up” to the throttle setting and 1-2 seconds to “spool-down” to idle, before the reversers are stowed.

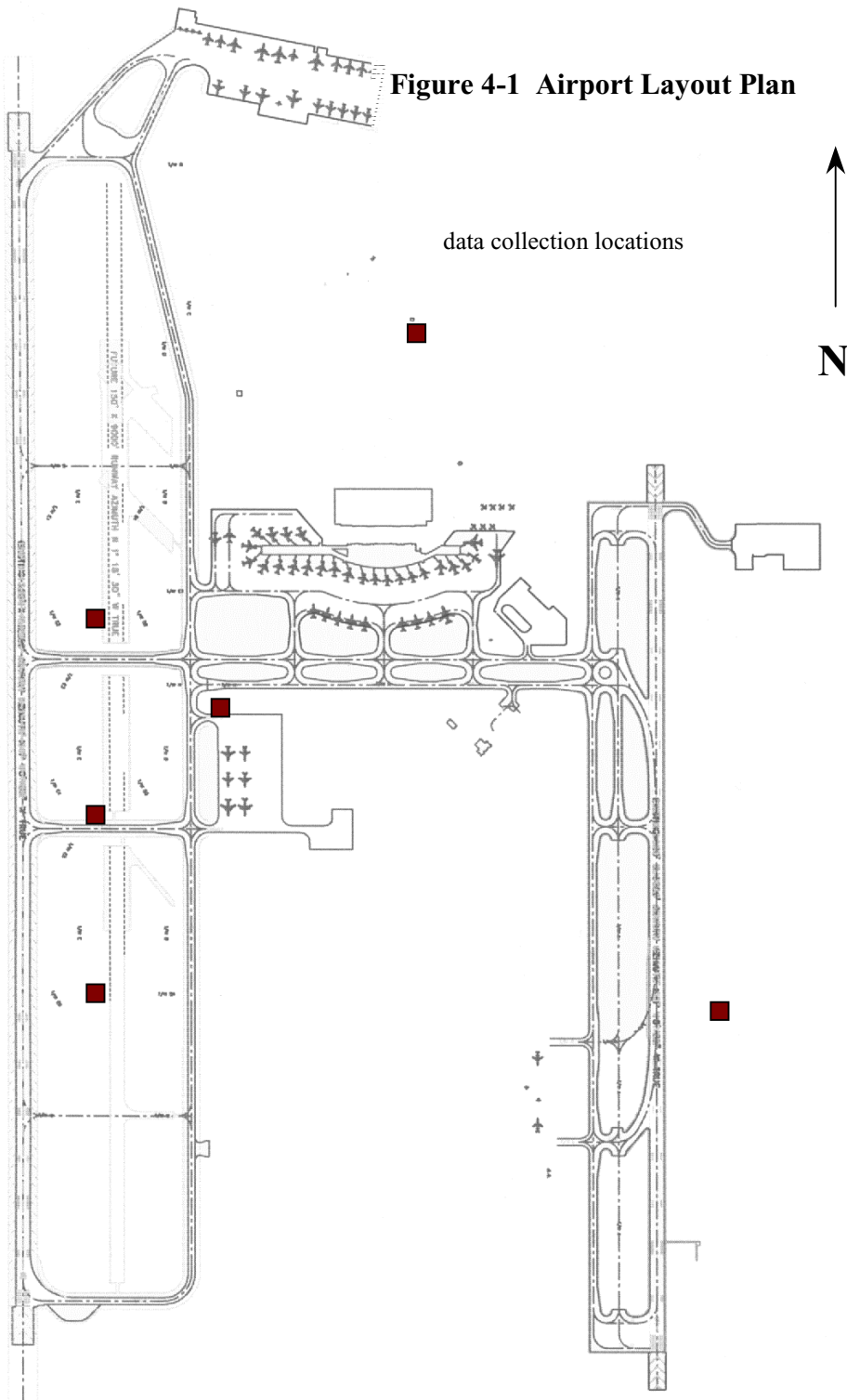
An airport layout plan of ABIA is shown in Figure 4-1, which displays the data collection locations selected. Because of FAA security requirements, an escort by airport personnel was required at all times to visit the airfield. Most camcorders currently available can record for a maximum of 4 hours. To reduce the frequency of tape-changing trips to the airport, it was desirable to minimize the number of tape changes necessary. This led to the development of a specially-designed data collection station.

#### **4.6 DATA COLLECTION STATION**

To maximize the length of time between tape changes, a VCR was chosen as the recording device. Using a VCR resulted in 8 hours worth of continuous data. Next, a camera which provided a continuous video-audio feed that could be patched into a VCR had to be found. Most modern camcorders will not act as a “dummy camera” and provide both video and audio feed for more than 5 minutes without recording. This is known as the “stand-by mode”. A camcorder which was able to remain in standby mode indefinitely was borrowed from the Construction Industry Institute at the University of Texas.

A mobile power supply was another important feature of the data collection station. A heavy-duty 12 volt marine battery was used. A power inverter was used to run the VCR and a 9 volt power adapter was used to run the camcorder. Although the camcorder could have been powered by the inverter also, the 9 volt adapter was chosen to minimize the voltage conversion, thereby increasing power efficiency. The batteries supplied enough power for approximately 24 hours of data collection. Each battery was charged on alternate nights. Photos of the data collection station are shown in Figures 4-2 and 4-3.

**Figure 4-1 Airport Layout Plan**



**Figure 4-2 East Runway Data Collection Station**



**Figure 4-3 West Runway Data Collection Station**



#### **4.7 AIRLINE SCHEDULE**

In November 2000, 124 weekday arrivals were scheduled into ABIA. The time distribution of arriving aircraft is shown in Table 4-7. There are two distinct daily peaks, between 4 and 5 PM and between 9 and 10 PM. Due to the darkness on the airfield, data collection would be limited to daytime hours. In late November, sunset occurs at approximately 5:45 PM. To maximize data collection efficiency during the daytime, videotaping was restricted to a single 8-hour shift, from approximately 9:30 AM to 5:30 PM.

**Table 4-7 ABIA Hourly Arrivals**

time	arrivals
700-800	4
800-900	5
900-1000	6
1000-1100	5
1100-1200	9
1200-1300	4
1300-1400	9
1400-1500	7
1500-1600	8
1600-1700	13
1700-1800	8
1800-1900	6
1900-2000	5
2000-2100	7
2100-2200	13
2200-2300	9
2300-2400	4
>2400	2

#### **4.8 DATA COLLECTION PROCESS**

In order to study reverse thrust usage during landing, a video camcorder with a time/date stamp was needed to record landing aircraft. The camcorder's video would enable visual identification of the aircraft type and airline, while the audio would permit measurement of reverse thrust duration. Reverse thrust usage is easily noticed by the audible increase in engine for power-backing and just after main gear touchdown during landing.

Data collection for reverse thrust during power-backing was begun at ABIA during August 2000. A data collection station consisting of a Sony Handicam camcorder, marine battery, and DC power inverter were setup in the grassy area behind American Airline's gates. Data was collected for 4 days, from 7 AM to 7 PM and tapes were changed every 4 hours. After reviewing the video, approximately 50 observations were recorded. Since the number of observations recorded in August was smaller than the sample size needed, data for more powerbacks was collected in December.

Data collection for reverse thrust during landing was performed at Austin-Bergstrom International Airport during November 2000. Inclement weather during the months of October and November caused numerous delays in the data collection procedure. On the west runway, data collection stations were setup in one of three possible locations, depending on wind direction. During south flow, the station was setup near taxiway G, which is the first exit when landing to the south. During north flow, the station was setup near taxiway T, which is the first exit when landing to the north. On days where the winds were projected to shift from south to north or north to south, the station was setup between taxiways T and G. On the east runway, data was collected at the midpoint, near the east perimeter road. All data collection stations were located between 500 and 800 feet from the runway centerline. Data collection locations are identified in Figure 4-1.

The data collection stations were setup at the airport in the morning and removed in the evening. Initially, one data collection station was created and it was alternated between each runway. Later, to speed the process, an additional data collection station was implemented, to collect data on both runways simultaneously.

From the experimental design in Section 4-3, it was determined that a sample size of 624 aircraft would be needed. With 124 scheduled daily flights between the hours of 6 AM and 1 AM, ABIA handles an average of 6.5 landings per hour. Dividing the traffic between both runways, each runway handles a landing every 18 minutes, on average. During the data collection hours of 9:30 AM to 5:30 PM, 62 arrivals were estimated to occur, an average of 7.75 per hour. Using this arrival rate, 160 hours of data collection would be needed to obtain 624 observations. Data was collected on 12 days during the month of November and 5 days during early December.

#### **4.9 DATA REDUCTION**

After the data collection was completed, the data had to be reduced and prepared for analysis. This was performed by watching the videotapes, separating landings from takeoffs, and timing the duration of reverse thrust usage. When a landing occurred, the airline and aircraft were identified, while reverse thrust duration was timed with a stopwatch. The results were recorded by hand and later transferred to a computer spreadsheet.

During the data reduction, the videotapes were fast-forwarded between landings and played at normal speed when a landing occurred. As a result, the 3 hours of video could be analyzed during 1 hour of real-time. Including power-backing, 250 hours of video data were collected. The data reduction took approximately 80 hours to complete. A total of 655 landing aircraft were observed along with 79 powerbacks. The results of the data analysis are shown in Chapter 5.



## CHAPTER 5. DATA ANALYSIS

### 5.1 REVERSE THRUST USAGE DURING LANDING

To gather a preliminary understanding of the results, cross tabulations of the data were performed and distributions of the data were charted. Table 5-1 shows reverse thrust data grouped by aircraft/airline combination.

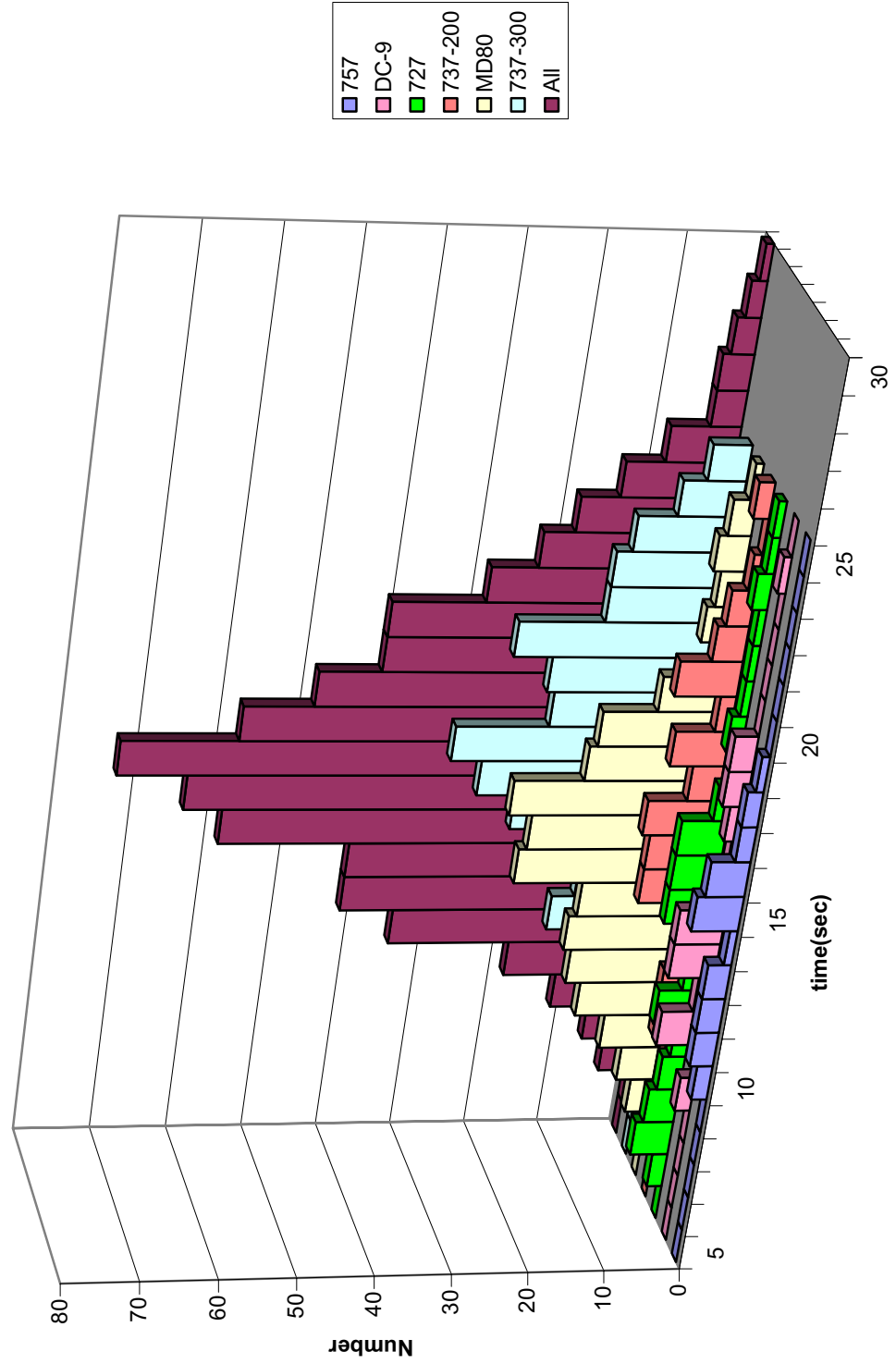
In each cell, the first number designates the number of observations of each airline/aircraft combination. The second number is the mean duration of reverse thrust usage for the respective combination. Cells with zero observations are empty cells, where the aircraft/airline combination was not observed.

Different airlines choose to operate different aircraft types. For example, Southwest Airlines only operates Boeing 737 aircraft: B737-200, B737-300, B737-500, and B737-700 series aircraft. Since B737-300 and later versions are grouped under one class, only two aircraft types contain observations for Southwest. Empty cells exist for all other airline-aircraft combinations for Southwest.

For this experiment, thrust reverse durations were collected audibly. The time interval measured corresponds with the period of increased engine thrust. Since increased engine thrust corresponds with increased emissions, this method is more accurate when estimating emissions associated with reverse thrust. In contrast, the UDRI data measures the total time between deployment and stowage. Figure 5-1 shows the distribution of thrust reverse usage by aircraft type.

Newer Boeing 737s (series 300 and later) are most frequently flown into ABIA, followed by MD-80s and older B737s. Southwest has the largest number of daily flights, with American following second. For all 655 landing observations, the average of thrust reverse usage was slightly less than 16 seconds. The B757, DC-9, and MD-80 were far below this average, while the B737s and B727s were at or above average. It appears that the majority of aircraft below the average have clamshell

**Figure 5-1 Distribution of Reverse Thrust Usage by Aircraft**



**Table 5-1 Reverse Thrust Usage by Aircraft/Airline**

	B737-300	B737-200	B757	B727-200	DC-9	MD-80	All
American	0 --	0 --	28 13.8	0 --	0 --	117 14.3	145 14.2
Continental	23 15.8	0 --	0 --	0 --	0 --	44 13.7	67 14.4
Delta	8 15.6	15 13.3	0 --	24 16.0	0 --	17 15.0	64 15.1
America West	15 19.5	0 --	0 --	0 --	0 --	0 --	15 19.5
Northwest	0 --	0 --	0 --	0 --	22 13.5	0 --	22 13.5
Southwest	189 17.2	50 16.7	0 --	0 --	0 --	0 --	239 17.1
TWA	0 --	0 --	0 --	0 --	12 13.6	6 12.3	18 13.1
United	24 16.5	0 --	0 --	18 21.0	0 --	0 --	42 18.4
Unknown	8 17.4	4 19.0	0 --	0 --	1 23.1	15 17.6	28 18.0
Cargo	0 --	0 --	0 --	14 19.0	1 26.8	0 --	15 19.5
All	267 17.1	69 16.1	28 13.8	56 18.4	36 14.0	199 14.4	655 16.0

reversers, while aircraft above the average have cascade reversers. This was expected, due to the increased efficiency of the clamshell design.

In order to generate statistically significant conclusions on the factors influencing thrust reverse usage, analysis of variance was performed on the data. Analysis of variance must be performed when more than two groups of data are compared. It allows the factors influencing reverse thrust to be isolated. It also allows partitioning of variance between and within aircraft and airline groups and enables the monitoring of interactions between airlines and aircraft.

For this experiment, one-way ANOVA was initially performed on the data, grouping by aircraft type only. The results are shown in Table 5-2.

**Table 5-2 ANOVA by Aircraft Type**

Source of Variation	SS	df	MS	F <sub>0</sub>	P-Value
Aircraft	1406.2	5	281.2	17.96	<0.001
Error	10161.7	649	15.7		
Total	11567.9	654			

F<sub>0</sub> is the test statistic for the hypothesis of usage varying across aircraft type. It is the ratio of mean-squared aircraft to mean-squared error and is an F distribution with a-1 and N-a degrees of freedom (Montgomery, 1997). Since  $F_{0.05,5,649} = 2.21$ ,  $F_0 > F$  and H<sub>0</sub> is rejected. This indicates that there is significant variation by aircraft type.

Next, the airline factor is introduced to the model. As shown by the graphs previously presented, there appears to be interaction among aircraft-airline combinations. For this analysis, cargo airlines were removed because of their low frequency of operation. During the data collection, only 14 landings of cargo aircraft were recorded among several cargo airlines. Aircraft with airlines designated as “unknown” were also removed. This reduced the dataset to a size of 612 observations, from 655. Table 5-3 shows the results of the two-way ANOVA. In SAS, normal sum of squares are shown as Type I SS and adjusted sums of squares are shown under Type III SS.

**Table 5-3 Two-way ANOVA by Aircraft and Airline**

Source of Variation	SS	Adj SS	df	MS	F <sub>0</sub>	F <sub>0.05,v1,v2</sub>
Aircraft	1463.2	232.5	5	47.5	3.55	2.21
Airline	454.1	407.4	7	58.2	4.35	2.01
Aircraft*Airline	134.5	134.5	3	44.8	3.35	2.60
Error	7969.2	7969.2	596	13.37		
Total	10021.0		611			

The results show that F<sub>0</sub> is greater than F<sub>α,v1,v2</sub> for all sources of variation. This indicates that aircraft, airline, and the interaction between the two do significantly influence thrust reverse usage. Due to the number of empty cells, only six aircraft-airline cells for the interaction could be analyzed, containing four different airlines and four aircraft types. This occurs as there are

only two airlines which operate the same two aircraft types. United and Delta both operate B727 and B737 aircraft.

To gather more information on the influence of aircraft-airline combination on thrust reverser usage, more analyses were needed. Since several carriers operate B737-300 and MD-80 aircraft, one-way ANOVA was performed individually on these aircraft types, isolating the variance by airline. T-tests were performed to compare pairs of airlines operating same aircraft types.

The results of individual aircraft ANOVA are shown in Tables 5-4 through 5-7. For MD-80 aircraft, the predominant carrier is American, followed by Continental, Delta, and TWA. The ANOVA results show that reverse thrust usage for MD-80 aircraft does not vary significantly by airline.

**Table 5-4 MD-80 Thrust Reverse Usage by Airline**

Airline	Number	Mean	$\sigma$
American	117	14.3	3.47
Continental	44	13.7	3.76
Delta	17	15.0	5.23
TWA	6	12.3	3.14

**Table 5-5 Analysis of Variance for MD-80 Aircraft**

Source of Variation	SS	df	MS	$F_0$	$F_{0.05, v_1, v_2}$
Airline	45.4	3	15.1	1.09	2.60
Error	2490.6	180	13.8		
Total	2356.1	183			

One-way ANOVA was also performed on B737-300 aircraft separately. Southwest dominates the B737-300 category, followed by Continental, America West, and Delta. The results show that airline does influence thrust reverse usage for the B737-300.

**Table 5-6 B737-300 Thrust Reverse Usage by Airline**

Airline	Number	Mean	$\sigma$
Southwest	189	17.2	3.72
Continental	23	15.8	3.79
America West	15	19.5	3.39
Delta	8	15.6	3.71

**Table 5-7 Analysis of Variance for B737-300 Aircraft**

Source of Variation	SS	df	MS	F <sub>0</sub>	F <sub>0.05,v1,v2</sub>
Airline	146.5	3	48.8	3.56	2.60
Error	3173.2	231	13.7		
Total	3319.7	234			

Based on the results of the t-tests, we see that the means are significantly different for the B727-200 and the B737-200. The means are the same for airlines operating the DC-9, reflecting the similarity with the MD-80. The results of the t-tests are shown in Table 5-8.

**Table 5-8 Comparisons Between Airlines Operating Same Aircraft Types**

Aircraft	Airline	n	$\mu$	$\sigma$	t <sub>0</sub>	t <sub>0.025,n1+n2-2</sub>	result
B727-200	Delta	24	16.04	4.54	-3.74	2.02	reject H <sub>0</sub>
	United	18	20.96	3.74			
B737-200	Delta	15	13.29	3.04	-3.10	2.00	reject H <sub>0</sub>
	Southwest	50	16.73	3.96			
DC-9	Northwest	22	13.47	3.00	0.11	2.04	accept H <sub>0</sub>
	TWA	12	13.58	2.45			

## 5.2 ANALYSIS OF POWER-BACKING DATA

NOx emissions are also produced during the power-backing of aircraft away from boarding bridges. Data was collected for 79 powerbacks of American Airlines' MD-80s at ABIA. The mean duration for reverse thrust usage during power-backing was found to be 43.8 seconds, with a standard deviation of 5.5 seconds. The 95% confidence interval for power-backing ranges from 42.6 to 45.0 seconds. Since only one airline and one aircraft type perform power-backing at ABIA, analysis of variance is not necessary.

**Table 5-9 Powerbacks By Gate**

Gate	Count	Mean
14	24	43.76
15	34	43.81
17	18	44.28
All	76	43.91

Table 5-15 shows the power-backing results, separated by gate. The most number of powerbacks were recorded from gate 15, followed by gates 14 and 17. It also appears that the duration of power-backing does not vary significantly across gate. Although a total of 79 powerbacks were recorded, only 76 are shown Table 5-15. For three powerbacks, the gate was not noted during the data reduction.

### **5.3 CONCLUSIONS**

Based on the results of the data collection, a TIM for reverse thrust during landing should be 16.0 seconds for ABIA. The 95% confidence interval for reverse thrust usage ranges from 15.7 seconds to 16.3 seconds. Although some of the variation in thrust reverser usage during landing is explained by thrust reverser type, aircraft type, airline, and direction, the majority of the variation is influenced by other factors, which may not have been measured by this experiment. Approach speed, aircraft weight, and touchdown location may also have an impact on thrust reverser usage. These parameters could not be evaluated with the method of data collection used for this experiment. Additionally, reverse thrust is used in combination with wheel brakes to slow an aircraft. Information on actual brake usage during the landing roll is also needed, to assess the relationship between brake usage and reverse thrust usage.

During power-backing, reverse thrust is used for an average of 44 seconds. Reverse thrust usage during power-backing varies much less than usage during landing. This is indicated by the lower mean-to-standard deviation ratio. This occurs as power-backing is conducted in a more controlled environment than landing. Power-backing always starts at the same position, adjacent to the boarding bridge. During landing, the location of thrust reverser deployment depends on the touchdown location. Secondly, wing-walkers accompany the plane when power-backing to aid the pilot. They inform the pilot when he has backed up a sufficient distance.



## CHAPTER 6. FORECASTING

Emissions estimates from reverse thrust were developed for selected Texas commercial service airports for years 1996 and 2007 in areas which are currently exceeding or projected to exceed the NAAQS for ozone. These areas included the Houston-Galveston area, Dallas/Ft. Worth, and Austin. The selected airports in these areas included Bush Intercontinental (IAH), Houston Hobby (HOU), Dallas/Ft. Worth International (DFW), and Austin/Bergstrom International (AUS). Traffic counts and fleet mix data for the airports selected were obtained from the Federal Aviation Administration. The base year was selected to be 1996, which corresponds with base year in DFW Airport's Emissions Inventory and for TNRCC's Attainment Demonstration modeling. The year 2007 was selected as it is designated the year in which the Houston and Dallas areas must achieve attainment status.

### 6.1 TIME-IN-MODE

Table 6-1 shows reverse thrust usage by aircraft type during landing at ABIA. As discussed in the previous chapter, reverse thrust was used for an average of 16.0 seconds during landing and 43.8 seconds during power-backing. Although all aircraft types manufactured were not sampled by this study, it is assumed that the reverse thrust usage was similar for the unsampled aircraft types. The aircraft sampled by this study represent roughly 70% of the world's commercial aircraft fleet.

**Table 6-1 Reverse Thrust Usage by Aircraft Type, during landing**

Aircraft Type	Duration (sec)
B737-300/NG	17.1
B737-200	16.1
B757	13.8
B727	18.4
DC-9	14.0
MD-80	14.4
ABIA Mean	16.0

In order to develop a reverse thrust TIM for landing at DFW, a weighted average was developed based on the airport's fleet mix. A TIM for each aircraft type was assigned based on the data collected from ABIA. If the aircraft was not sampled at ABIA, its TIM was based on its thrust reverser classification. As discussed in Chapter 5, cascade reversers were used for an average of 16.4 seconds, while clamshell reversers were used for an average of 15.1 seconds. For power-backing, the computation of a weighted mean was not possible, since MD-80s were the only aircraft type sampled at ABIA. Therefore, it was assumed that all power-backs have the same duration at DFW.

For DFW, the weighted average of thrust reverse usage during landing was found to be 15.4 seconds. The usage at DFW was slightly less than ABIA because of the increased amount of MD-80 traffic. In 1996, nearly half of the traffic at DFW were MD-80s, which have clamshell reversers. In Austin, MD-80s represent less than one-third of the total traffic. The full edition of the Airport Activity Statistics was not published for the year 1996. Therefore, traffic data for DFW was obtained using the Airport's 1996 Emissions Inventory. Table 6-2 shows the commercial jet traffic at DFW in 1996 and the corresponding thrust reverse usage during landing.

**Table 6-2 DFW Commercial Jet Traffic 1996**

Aircraft	LTO	t-r time
A300-B4-200	537	16.4
A310-200	537	16.4
A320-200	948	16.4
A340-300	537	16.4
B727-200	40058	18.4
B737-200	11570	16.1
B737-300	5878	17.1
B737-400	2444	17.1
B747-200	294	16.4
B757-200-RR	22118	16.4
B757-200-PW	9947	13.8
B767-200	4367	16.4
B767-300	4367	16.4
DC 10-30	4223	16.4
DC8-51	1732	16.4
DC8-70	2043	16.4
DC9-10	15860	14
FOKKER 100	35799	15.1
L-1011-150	815	16.4
L-1011-200	815	16.4
MD-11	2103	16.4
MD-80-82	149985	14.4
MD-90-10	7589	16.4
Total	324566	15.4

## 6.2 EMISSIONS FACTOR FOR REVERSE THRUST

Based on the results provided by Skinn et al (1998), a median power-setting of approximately 80% N1 is used during reverse thrust for landing on the B737-400 and B767-200. Figure 6-1 shows a histogram of maximum power settings during thrust reverse for a B737-400. These results are consistent with Yetter (1995), which reported power settings during thrust reverse of 70-80%.

Breakaway thrust is the amount of thrust needed to initiate motion for a taxiing aircraft. Pilots report the power-setting for breakaway thrust to be approximately 30% for forward motion (Wilkes, 2000). As discussed in Section 2.4, clamshell thrust reversers are between 30 and 40%

effective. Given this information, a power-setting of approximately 85% is needed to begin motion for power-backing.

Aircraft engine emissions factors are published for only four modes of operation. In Baughcum et al (1996), it is suggested that the relationship between the power settings for which emissions factors are provided is linear. Using this assumption, an emissions factor for any power setting can be computed. Figure 6-2 shows NO<sub>x</sub> emissions factors for the JT8D-217 engine, used on the MD-80. The NO<sub>x</sub> emissions factor at climbout (85%) is 20.6 g/kg. The emissions factor for approach (30%) is 9.1 g/kg. The emissions factor for reverse thrust at 80% lies between the emissions factors for climbout and approach. Using linear interpolation, it was found that a power-setting of 80% has a NO<sub>x</sub> emissions factor of 19.6 g/kg for the MD-80.

**Figure 6-1**

Max N1 while TR Deployed 737-400

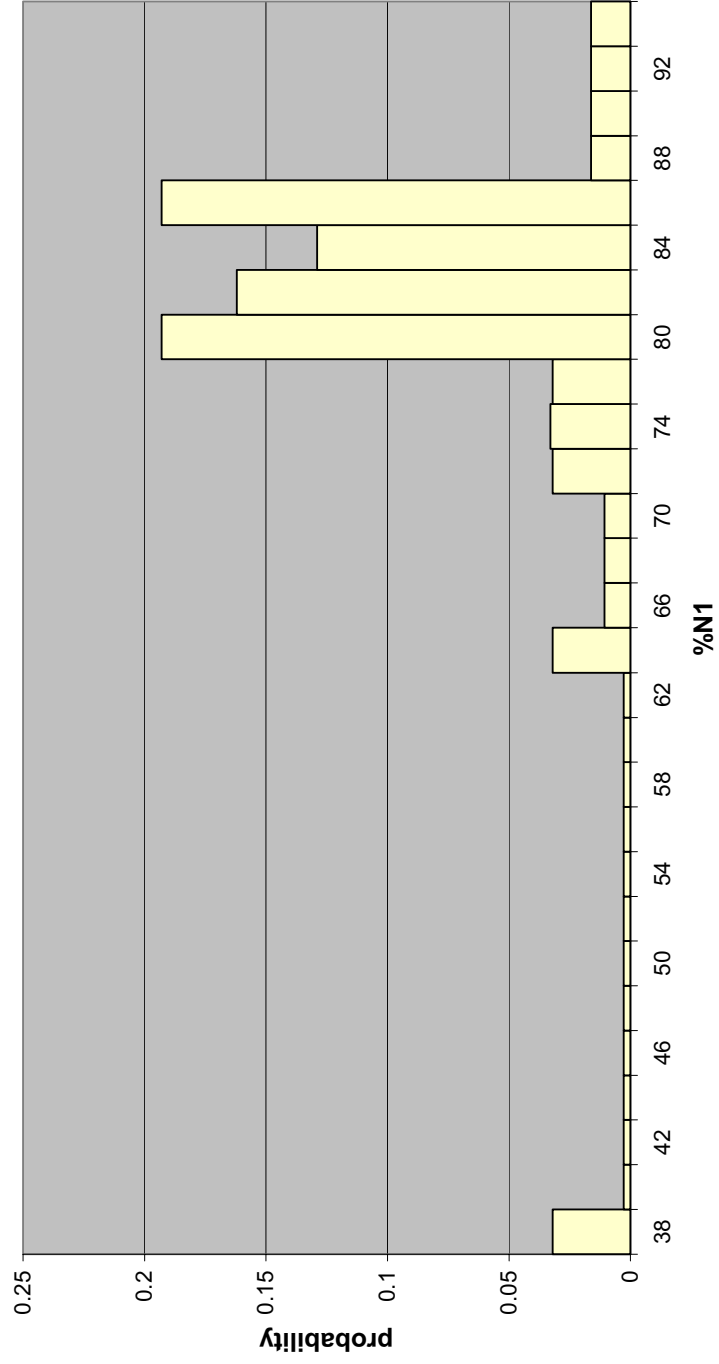
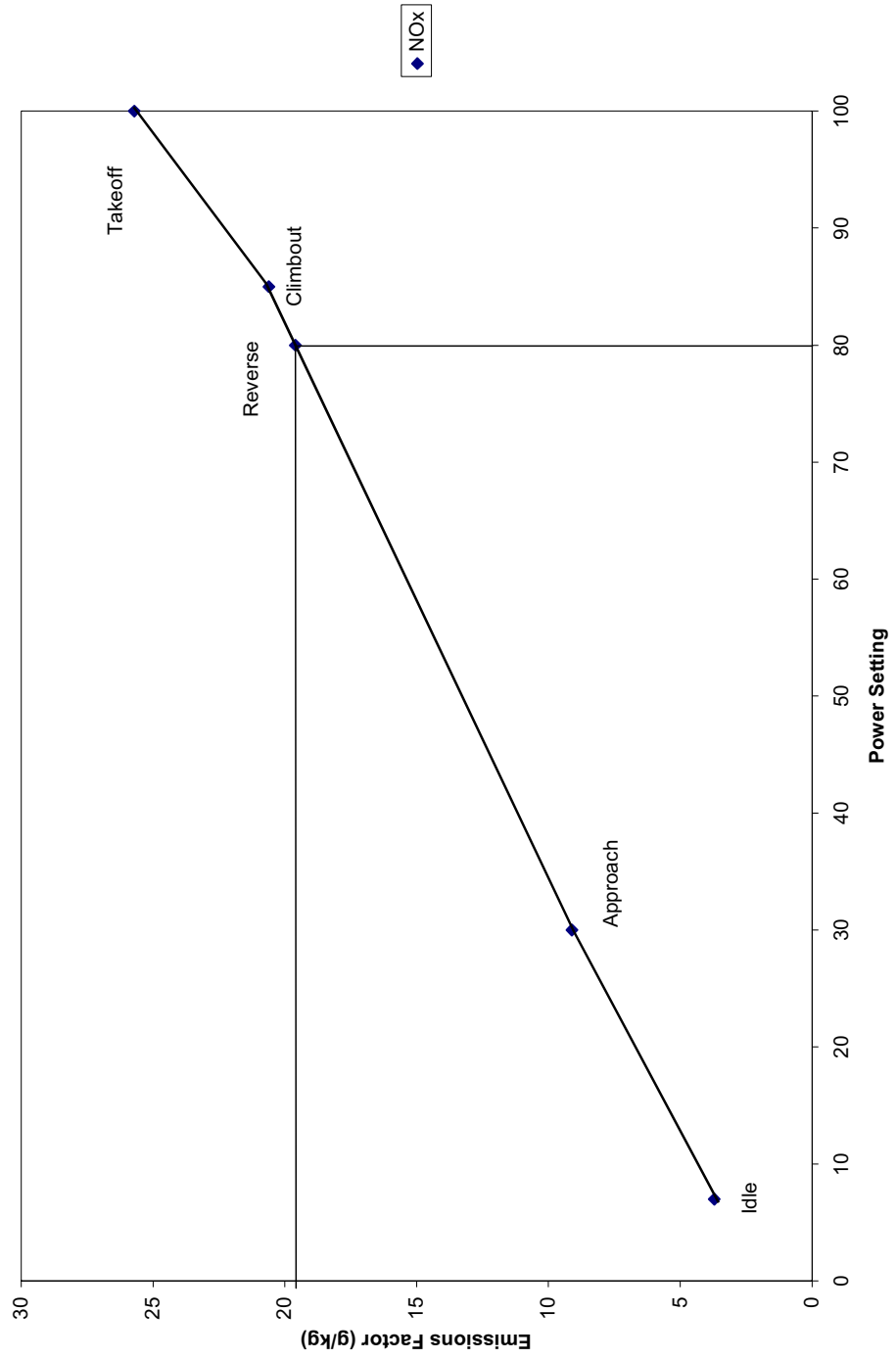


Figure 6-2

### Interpolation of Emissions Factors for JT8D-217 Engine



### 6.3 FLEET MIX AND TRAFFIC FORECASTS

Aggregate traffic counts for each of the airports were obtained from the FAA's Terminal Area Forecasts. For reverse thrust, operations of large jet aircraft only were considered. Commuter aircraft and regional jets were not included because of their minimal impact on emissions. The Terminal Area Forecasts provide current and future estimates for four categories of aircraft operations: air carrier, air taxi, general aviation, and military. Air carrier operations consist of flights by large jets only. Air taxi includes commuter aircraft, both turboprops and regional jets. General aviation includes private aircraft, while military includes all military aircraft.

Between 1996 and 2007, growth in jet traffic ranged from nearly 64% in Austin to 22% at DFW. Table 6-3 shows overall traffic growth at the Texas airports selected for the study.

**Table 6-3 Growth in Large Jet LTOs at Selected Texas Airports**

	1996 LTO	2007 LTO	growth
DFW	324,566	381,070	17.4%
IAH	138,682	204,348	47.3%
HOU	55,161	68,182	23.6%
DAL	49,754	70,902	42.5%
AUS	38,359	62,785	63.7%

As discussed in 6.1, the same fleet mix used in the 1998 DFW Airport Emissions Inventory was also used to compute the airport's emissions from reverse thrust. For airports other than DFW, fleet mix information was obtained courtesy of the Texas Transportation Institute (TTI), who also developed 1996, 1999, and 2007 emissions inventories for all Texas airports (Borowiec, Qu, and Bell, 2000). TTI provided the aircraft counts for each of the airports studied in electronic format which were used in their study. TTI obtained their fleet mix data from the Bureau of Transportation Statistics database. TTI assumed that the fleet mix at the major airports would remain the nearly same in 2007. This is a valid assumption, as there is uncertainty in predicting future airline fleet mixes. For this study, the airlines contacted refused to release their future fleet data beyond the year 2003. Secondly, airport emissions inventories

are more sensitive to the number of LTOs than aircraft fleet mix. Although many older aircraft with Stage 2 engines were phased out by the year 2000, many of the airlines have opted to “hush-kit” aircraft and continue operating them.

#### 6.4. DEVELOPMENT OF REVERSE THRUST EMISSIONS FORECASTS

As discussed previously, aircraft emissions factors are expressed in grams of pollutant produced, per kilogram of fuel burned for each mode of operation. To compute emissions, the emissions factor is multiplied by the fuel consumed during each phase of operation for each aircraft. During reverse thrust, fuel flow at a power setting of 80% must first be computed. Fuel flow is proportional to the engine’s power setting. At a power-setting of 80%, fuel flow is 80% of the flow at takeoff or full thrust. Multiplying the fuel flow by the TIM, number of engines, and number of LTOs, the emissions from reverse thrust are obtained for each aircraft type. Summing by aircraft type yields the total reverse thrust emissions during landing.

Table 6-4 shows a summary of the reverse thrust emissions estimates during landing, for 1996 and 2007.

**Table 6-4 Reverse Thrust Emissions Estimates during Landing**

Airport	1996		2007	
	LTOs	NOx (tons/yr)	LTOs	NOx (tons/yr)
DFW	324566	225	381070	263
IAH	138682	72	204348	106
HOU	55161	23	68182	28
DAL	49754	21	70902	30
AUS	38359	19	62785	31

Austin and DFW were the only airports studied where power-backing is practiced. At DFW, American Airlines power-backs its aircraft whenever possible to minimize ground crew personnel and aircraft tow usage. American operates 64 gates at DFW and power-backs are permitted at 40 of the 64 gates. The only aircraft which are capable of being power-backed are MD-80s, F-100s and Boeing 727s, which represent 85% of American’s traffic. In 1996, American operated 520 daily departures from DFW. This indicates that roughly 300 aircraft were “power-backed” daily at DFW Airport. Aircraft power-back emissions estimates for DFW and Austin are shown in Tables 6-5 and 6-6.

**Table 6-5 Powerback Emissions Estimates for DFW**

Aircraft	Number of Annual Powerbacks	NOx Emissions per Powerback (kg)	Annual NOx Powerback Emissions (tons)
MD-80	70236	1.83	128.5
B727-200	9398	1.66	15.6
F100	19197	0.72	13.8
Total	98831		157.9

The MD-80 generates the highest amount of NOx per power-back. Even though the B727 has 3 engines, it generates less NOx than the MD-80 during a powerback. The MD-80's engines were developed nearly 20 years after the B727's engines. Historically, improvements in fuel efficiency have resulted in higher aircraft engine NOx levels (Moxon, 2000). However, as aircraft and their contribution to air quality have received more attention, aircraft engine manufacturers have begun focusing on aircraft engine NOx reduction. This is shown by the reduction in NOx produced by the Fokker F-100's engines, as it is the newest aircraft which can be power-backed.

In Austin, American operated 3 gates at Robert Mueller Municipal Airport in 1996. Although data was collected at Austin/Bergstrom International Airport, with MD-80s only, it was assumed that powerback emissions have remained constant since 1996, because of the small quantity of emissions.

**Table 6-6 Powerback Emissions Estimates for Austin**

Aircraft	No of Annual Flts	NOx Emissions per Powerback (kg)	Annual NOx Powerback Emissions (tons)
MD-80	4745	1.83	8.7

To compute aircraft tow emissions, the tow operating time for narrowbody aircraft was assumed to be 6 minutes per LTO, which is the EDMS default. For power-backing, engines were assumed to operate at 80% power for 44 seconds. As shown by Table 6-7, towing an aircraft back instead of power-backing reduced NOx emissions by nearly 1.7 kg per departure, a reduction of 92% over power-backing. The aircraft tow emissions were subtracted from the

powerback emissions to show the net effect of power-backing. The results are shown in Table 6-8. At DFW, with 280 aircraft power-backed daily, eliminating power-backing would reduce NOx by slightly less than one-half ton per day or 143 tons per year.

**Table 6-7 Emissions Comparison for Powerback vs. Towback**

Source	Emissions kg/LTO		
	CO	HC	NO <sub>x</sub>
Towback (diesel)	0.0056	0.0168	0.154
Powerback	0.119	0.042	1.834
Difference	-52.9	-60%	-92.3%

**Table 6-8 Net Powerback Emissions Estimates for DFW and ABIA (tons/yr)**

Airport	Powerback	Aircraft Tow	Net Result
DFW	157.9	15.2	142.7
Austin	8.7	0.7	8.0

Initially, the emissions from reverse thrust were computed for the selected airports for the year 1996. To forecast emissions for the year 2007, the emissions were scaled up by the projected level of traffic growth. For power-backing, emissions were estimated to remain constant. Production has ceased on the aircraft which American Airlines currently powerbacks. These include the MD-80, B727, and F-100. According to the Airport Activity Statistics, the total number of flights by rear-engined aircraft at DFW has remained approximately the same since 1996.

After computing the annual emissions associated with reverse thrust during landing and power-backing, a conversion factor was developed to generate totals in tons per day. Air travel demand is lowest on Saturdays and activity was assumed to be reduced by 25%. With this assumption, the annual totals are converted to tons per day by dividing by 351. Results are shown in Table 6-9.

**Table 6-9 Emissions from Reverse Thrust at Texas Airports (tons/day)**

Airport	1996			2007		
	Landing	Powerback	Total	Landing	Powerback	Total
DFW	0.64	0.41	1.05	0.75	0.41	1.16
IAH	0.21	---	0.21	0.30	---	0.30
HOU	0.07	---	0.07	0.08	---	0.08
DAL	0.06	---	0.06	0.09	---	0.09
AUS	0.05	0.02	0.08	0.09	0.02	0.11

In the case of DFW Airport, eliminating reverse thrust is equivalent to removing more than 22,000 cars from the road on a daily basis. This assumes a composite vehicle emissions factor of 1.81 grams of NO<sub>x</sub> per mile and that each car is driven an average of 30 miles per day (Rice, 1999).

Austin and DFW are among the only airports in Texas which allow power-backing of aircraft. At the other airports included in this study, power-backing is not allowed for safety reasons. Emissions from power-backing represent a significant source of reverse thrust emissions. In 1996, power-backing was responsible for more than 40% of the NO<sub>x</sub> emissions from reverse thrust at Austin and DFW. In 2007, the proportion of NO<sub>x</sub> from power-backing decreases at both airports due to the growth in use of other aircraft types.

Growth in emissions is directly related with growth in air travel. Austin leads the group in growth percentage between 1996 and 2007. This is primarily due to the region's growth and available runway capacity at ABIA. Operations at Houston Intercontinental are projected to increase by nearly 50% in 2007. This increase can be attributed to Continental Airlines' growth and the addition of a third widely-spaced parallel runway, which will allow triple simultaneous instrument approaches.

## **6.5 CONCLUSION**

Reverse thrust was found to have the largest impact at DFW Airport. This is because of the sheer number of aircraft operations and the practice of power-backing by American Airlines. In 2007, DFW is projected to handle nearly double the traffic IAH handles. In terms of the number of flights, the increase in operations at DFW and IAH is similar. Between 1996 and 2007, DFW will add 56,000 jet LTOs, while IAH will add 65,000 LTOs. The difference in

reverse thrust emissions between IAH and DFW is more pronounced, a nearly 4:1 ratio, as power-backing is not practiced at IAH.

## **CHAPTER 7. AIR QUALITY EFFECT OF REVERSE THRUST**

### **7.1 OZONE AS A POLLUTANT**

Ozone (O<sub>3</sub>) is designated as a criteria air pollutant by the EPA. It is a photochemical oxidant, which is a secondary pollutant that is formed from a series of chemical reactions involving VOCs, NO<sub>x</sub>, the hydroxyl radical (OH), other radicals, and sunlight (Wark, Warner, and Davis, 1998). The aerosols formed during these reactions create a reduction in visibility, with a brownish tint. Ozone can cause cracking and hardening of tires, as well as reduced vegetation growth. Ozone can also cause respiratory problems. Individuals with chronic lung disease, such as asthma and emphysema, as well as the elderly and young children, are particularly sensitive to ozone (TNRCC Ozone, 2001).

### **7.2 MONITORING DATA**

Figure 7-1 shows the location of the EPA air quality monitors in the Dallas region. CAMS70 opened in Grapevine, just north of DFW Airport in August 2000. The station was opened to fulfill the EPA's Photochemical Assessment Monitoring Station (PAMS) requirements, which require states to develop monitoring networks in their non-attainment areas to better understand their ozone problems. (EPA PAMS, 2001). The program requires a minimum of five monitoring stations: one upwind station, one central city station to measure maximum precursor emissions, another station to measure maximum ozone concentration, and another station downwind. The prevailing winds during the summer in Dallas are from the Southeast. During ozone episodes, the majority of ozone precursors are emitted over the city of Dallas during the morning rush hour. Ozone formation begins to occur and peaks in the afternoon, as the plume drifts northwestward towards Denton, passing slightly north of DFW Airport. During the ozone season of 2001 (through September 15), the largest number of violations of the 8-hour standard occurred at C70. Station C56 in Denton follows next. Table 7-1 shows the number of 8-hour violations recorded at each station. In 2001, the Dallas stations recorded only 2 days above 125 ppb, which were August 3 and 4, 2001. C70 violated the 1-hour standard for two hours on August 4. The daily maximum for the region occurred three times at C70 and the hourly peak for the region was recorded at C70 on 27 occasions, when ozone levels



**Table 7-1 Summer 2001 Eight-hour Violations in Dallas Region, through 9/15/2001**

Station	Number
C70 Grapevine Fairway	18
C56 Denton Airport	16
C31 Frisco	14
C17 Keller	15
C75 Eagle Mountain Lake	12
C13 Ft. Worth Northwest	11
C73 Granbury	6
C76 Parker County	5
C68 Anna	3
C401 Dallas Hinton St.	3
C63 Dallas North No 2	3
C69 Rockwall	1
C74 Sunnyvale	1

### **7.3 AIR QUALITY MODELING**

For this study, the Comprehensive Air Quality Model with Extensions, Version 2.0 (CAMx) was used to model ozone concentrations resulting from the use of reverse thrust. CAMx is a photochemical grid model developed by the Environ Corporation. The episode selected for modeling was June 18-22, 1995. This episode is also used for the SIP modeling in Dallas. The model-ready input files were downloaded from TNRCC's FTP site. For this episode, TNRCC has a base case with 1995 emissions and a future case with 2007 emissions. For this study, only 2007 was modeled, as emissions from reverse thrust were projected to have the most significant effect then. Table 7-2 shows the maximum observed ozone concentrations and the simulated maximum using the 1995 base case on each date.

**Table 7-2 Maximum Ozone Concentrations Observed and Simulated Base Case**

Date	Observed Peak Ozone (ppb)	Simulated Peak Ozone (ppb)
06/18/95	77	74
06/19/95	113	113
06/20/95	119	131
06/21/95	144	134
06/22/95	135	139

TNRCC's preferred 2007 future base case is designated as *2007d* (TNRCC, 2000). In developing 2007d, an estimate of on-road mobile source emissions was obtained from the North Central Texas Council of Governments (NCTCOG). NCTCOG used a travel demand model with a projected 2007 roadway network and projected demographic information to predict vehicle emissions using MOBILE5. For non-road mobile sources, emissions were grown using projected population growth. For point sources, reductions of approximately 75% were implemented, based on recently passed legislation (TNRCC, 2000).

The 2007 case selected for modeling contains reduction measures associated with Strategy D30, contained in TNRCC (2000). Fifty-two strategies were modeled in TNRCC (2000). Strategy D30, the preferred strategy, contains a 55% reduction in NO<sub>x</sub> over present levels and a 34% reduction over the 2007d base case. A few of the emissions reduction strategies included in D30 are:

- 5 mph speed limit reduction
- reformulated gasoline
- California Low-Emission Vehicles
- 10 AM construction start
- Low NO<sub>x</sub> water heaters
- Electrification of Airport GSE

Table 7-3 shows a comparison of the emissions from 2007d Future Base and Strategy D30. Table 7-4 compares the simulated peak ozone levels, with and without Strategy D30. June 18-20 are omitted, as these days are needed for the episode to “ramp up”.

**Table 7-3 Comparison of 2007d Future Base and Strategy D30 Emissions**

Category	NOx (tons/day)		VOC (tons/day)	
	2007d future base	Strategy D30	2007d future base	Strategy D30
On-road mobile	207.9	157.2	135.4	130.4
Area/non-road mobile	176.3	128.3	304.4	296.1
Point sources	98.7	24.4	29.1	29.1
Biogenic Sources	26.6	26.6	257.9	257.9
Total	509.5	336.5	726.8	686.5

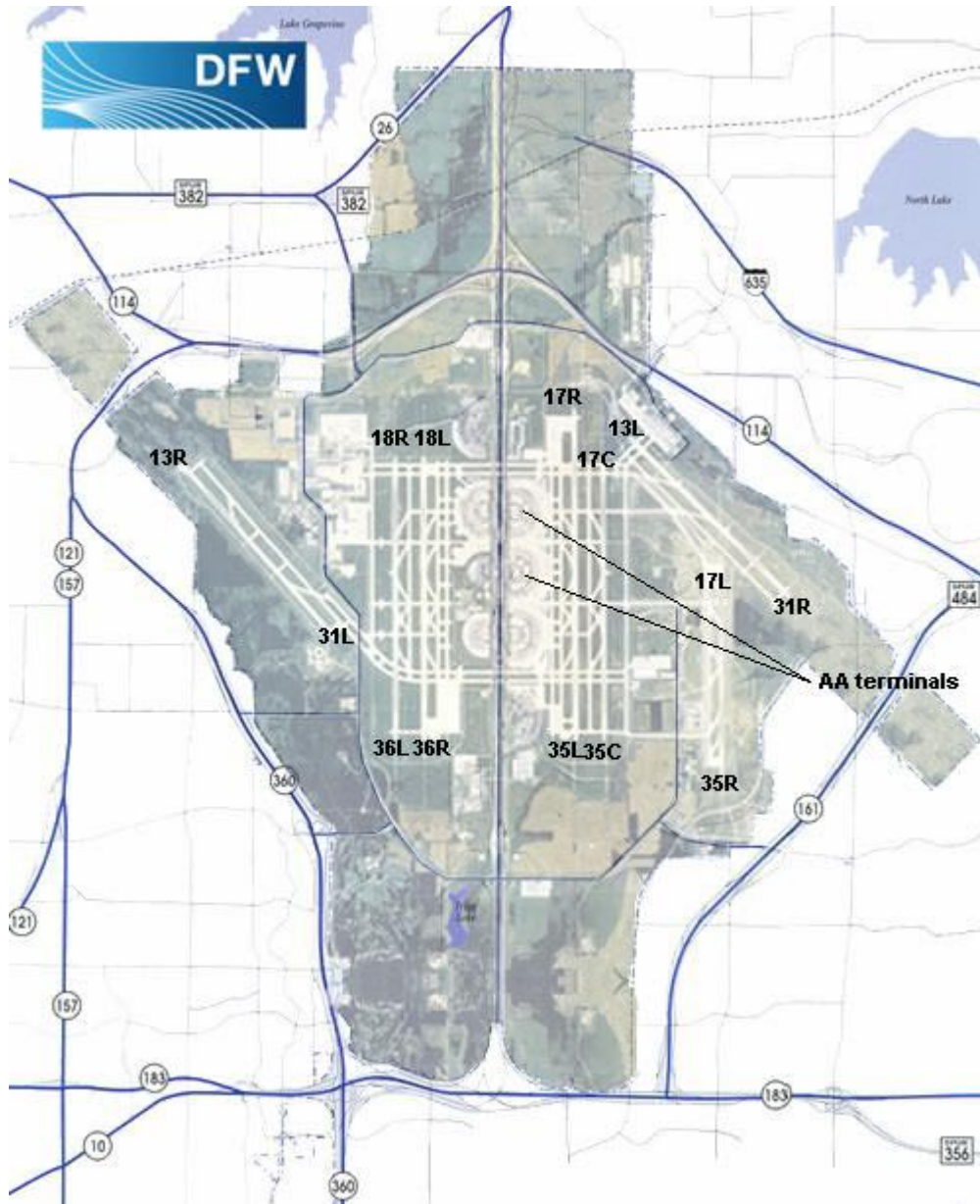
**Table 7-4 2007 Ozone Predictions**

Date	2007d Simulated Peak Future Base	2007 Strategy D30 Simulated Peak
6/21/95	122.4	113.3
6/22/95	126.7	115.9

The model used to simulate Strategy D30 contains 4 km x 4 km grid cells. The input files provided contain all of the meteorological and emissions data for an area which measures 232 km east-west and 200 km north-south, with Dallas/Ft. Worth roughly in the center.

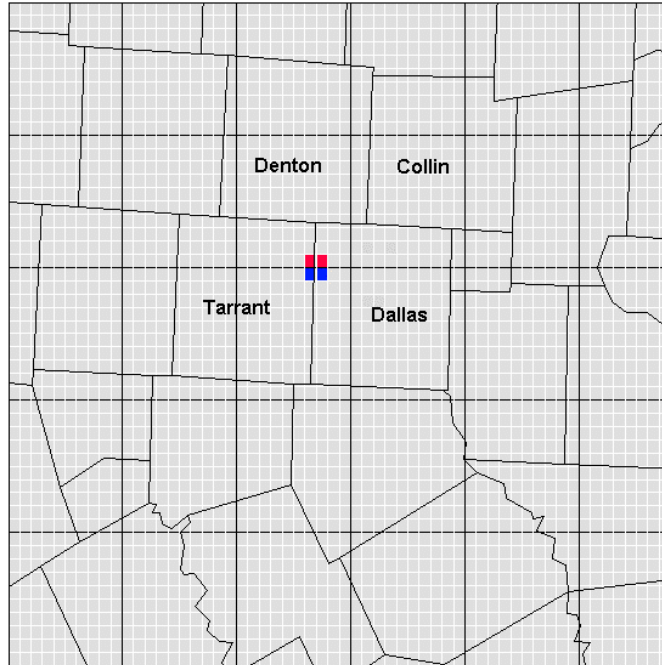
As previously discussed, current airport emissions inventories do not include emissions produced from reverse thrust. Reverse thrust is responsible for 1.2 tons per day of NOx emissions at DFW Airport. In order to simulate the effect of emissions from reverse thrust, the additional NOx must be added to the current model. To add the reverse thrust emissions, the grid cells where reverse thrust is used were located. Figure 7-2 shows the location of these grid cells. The grid cells in red show where reverse thrust is primarily used. DFW Airport covers a total 17,000 acres or 68 km<sup>2</sup>, an area slightly larger than 4 grid cells. The airport lies northwest of Dallas and northeast of Fort Worth; the Dallas/Tarrant County line bisects the airport. Although the airport covers four grid cells, reverse thrust is used primarily on the north half of the airport. American Airlines' gates are at the north end of the airport and reverse thrust is typically used during the first half of the landing roll. During the summer months, DFW Airport operates under south flow. Aircraft typically land on runways 17C, 17R, 18L, 18R, and 13R. An airport layout plan for DFW is shown in Figure 7-2.

Figure 7-2 Airport Layout for DFW Airport



source: DFW Airport Board

**Figure 7-3 Location of DFW Airport Grid Cells**



To add the emissions from reverse thrust, a masking factor was applied to the affected grid cells. Since the vast majority of NO<sub>x</sub> emitted is nitric oxide (NO), only the NO emissions were evaluated. In development of the model, TNRCC assumed the airport emissions to be divided across a multitude of grid cells. According to Jim MacKay, of TNRCC's Modeling Division, a total of 20.24 tons of NO<sub>x</sub> per day from aircraft are projected for the airport in 2007. Approximately 8.5 tons per day are emitted on the ground, during taxi and takeoff, while 9.7 tons per day are emitted during climbout. Two tons per day are emitted during approach. During approach and climbout, aircraft emissions are modeled as pseudo-elevated point sources, along a glideslope. A glideslope is defined as the horizontal distance traveled per unit of climb or descent. (Horonjeff, 1992). The elevated point sources used to model aircraft emissions during approach and climbout resemble a staircase. Twenty stacks are included during both approach and climbout. During approach, the first stack is located 100,000 feet (18.9 miles) away from the airport, at an elevation of 3,000 feet. The remaining stacks are spaced 5,000 feet apart, with a 3%

glideslope. For climbout, the first stack is located 2,500 feet from the airport centroid at an elevation of 300 feet. The last stack is located 25,000 feet from the airport at an elevation of 3,000 feet. The temporal distribution of aircraft emissions are modeled according to DFW's flight schedule.

Reverse thrust's effect on air quality is projected to be significant because the additional NOx which for a Pratt and Whitney JT8D-217 engine, used on an MD-80. Not including reverse thrust, approximately 63% of the aircraft NOx emissions are generated off-airport, during the climbout and approach phases. At DFW, reverse thrust increases the MD-80's on-airport NOx contribution by 58%.

**Table 7-5 NOx emissions from JT8D-217 engine, including reverse thrust**

phase	power setting	time (min)	NOx (g)	% of total
Takeoff	100%	0.7	1425	23.8%
Climbout	85%	2.2	2931	49.0%
Approach	30%	4.0	837	14.0%
Idle	7%	26	792	13.2%
Total			5985	100.0%
Powerback	80%	0.75	931	15.6%
Landing	80%	0.28	352	5.9%
Reverse Total			1283	21.5%

The masking factor was developed based on the reverse thrust emissions estimates of an additional 1.2 tpd for the airport. It was assumed that each of the two selected grid cells would be equally responsible for this increase. A factor of 1.44 was applied to these grid cells to obtain this increase. Table 7-6 shows the additional NO emissions from the selected grid cells. The masking was performed using a Fortran program named "Lomask", which was developed by Dr. Elena-McDonald Buller, of the Center for Energy and Environmental Resources at the University of Texas-Austin. After the masking was performed, the airport grid cells were checked, to ensure that the emissions were increased correctly.

**Table 7-6 NO Emissions from Selected Airport Grid Cells**

grid cell		NO (avg mol/hr)	NO (tpd)	Masking Factor	Add'l NO (tpd)
X	Y				
27	30	2607	1.9	1.44	0.83
28	30	1082	0.8	1.44	0.34
Total		3689	2.7		1.17

The Package for Analysis and Visualization of Environmental Data (PAVE), developed by the Microelectronics Center of North Carolina, was used to develop tile plots of the model runs to compare the results. The Base Case is the 2007 model run without reverse thrust. “RT2” is the model run with emissions from reverse thrust. The highest ozone concentrations occurred during the afternoon of June 22, between the hours of 12 and 4 PM. Figures 7-4 and 7-5 show the base case and RT2 on June 22 at 12:00. For both runs at 12:00, the highest ozone concentration is predicted to be 107 ppb over north central Dallas County.

Figures 7-6 and 7-7 show both runs for June 22 at 15:00. The plume of ozone drifts northwestward as prevailing winds are from the southeast. For both cases, the tile plots are nearly identical and a daily peak of 118 ppb occurs during this hour. In all O<sub>3</sub> tile plots, there is a distinct reduction in ozone levels near the airport, due to NO<sub>x</sub> scavenging. The prevalence of NO<sub>x</sub> scavenging near the airport is even more pronounced at 19:00. This will be discussed in further detail in Section 7.4. Figures 7-8 and 7-9 show both cases and Figure 7-10 shows a close-up of the ozone levels near DFW Airport.

At 19:00, ozone levels dip to as low as 6 ppb near the airport. Table 7-7 shows the ozone levels near the airport. Figure 7-11 shows the net difference in ozone concentrations between the two runs at 19:00 and Table 7-8 shows the difference in values of ozone concentrations resulting from the use of reverse thrust. As a result of NO<sub>x</sub> scavenging, ozone levels are sharply reduced at 19:00. The NO emitted by sources at the airport reacts with the already-formed ozone to produce NO<sub>2</sub>. Figure 7-12 shows the NO<sub>2</sub> concentration for the region and Figure 7-13 shows a close-up of NO<sub>2</sub> in the vicinity of the airport. The peak NO<sub>2</sub> for the Dallas region of 78 ppb occurs at the airport during this time. Figure 7-13 shows the difference in NO<sub>2</sub> with and without the use of reverse thrust. Table 7-9 shows the numerical NO<sub>2</sub> levels near the airport and the

difference in concentrations resulting from the use of reverse thrust. With reverse thrust, NO<sub>2</sub> levels are increased by as much 14 ppb at the airport.

**Figure 7-4 Base Case June 22, 12:00**

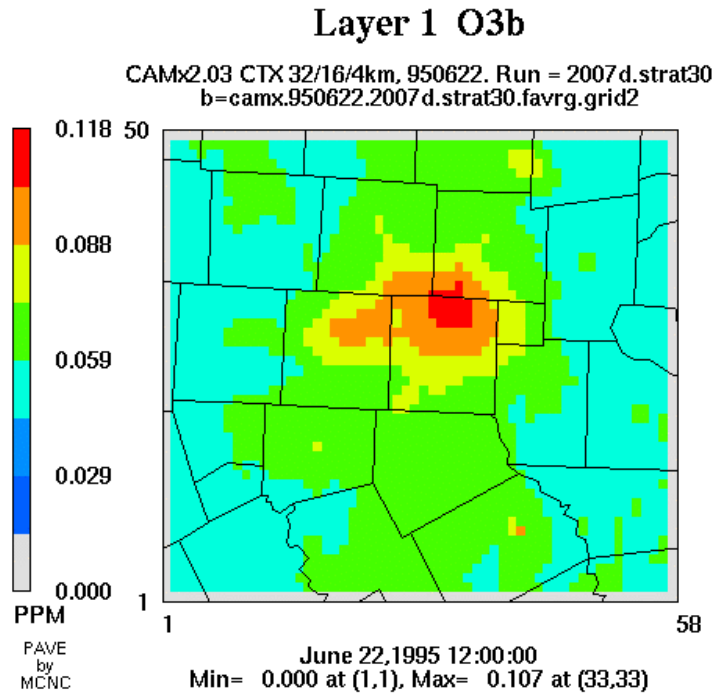


Figure 7-5 RT2 June 22, 12:00

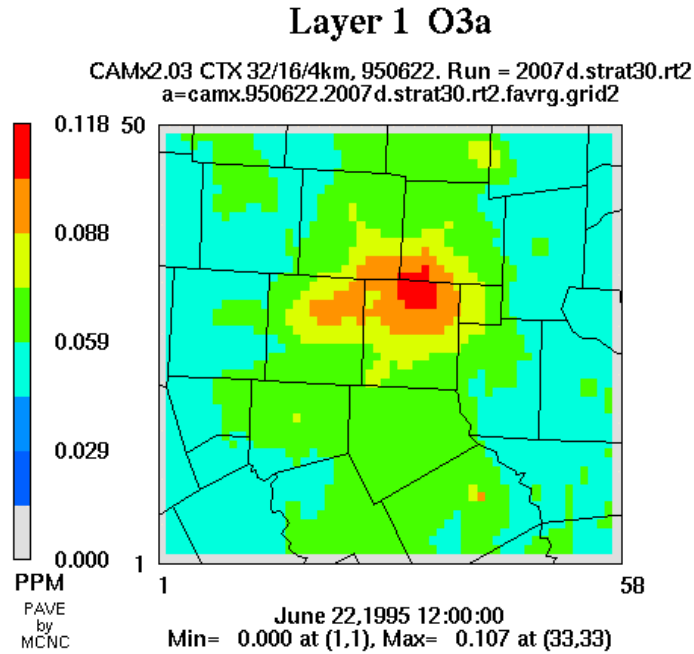


Figure 7-6 Base Case June 22, 16:00

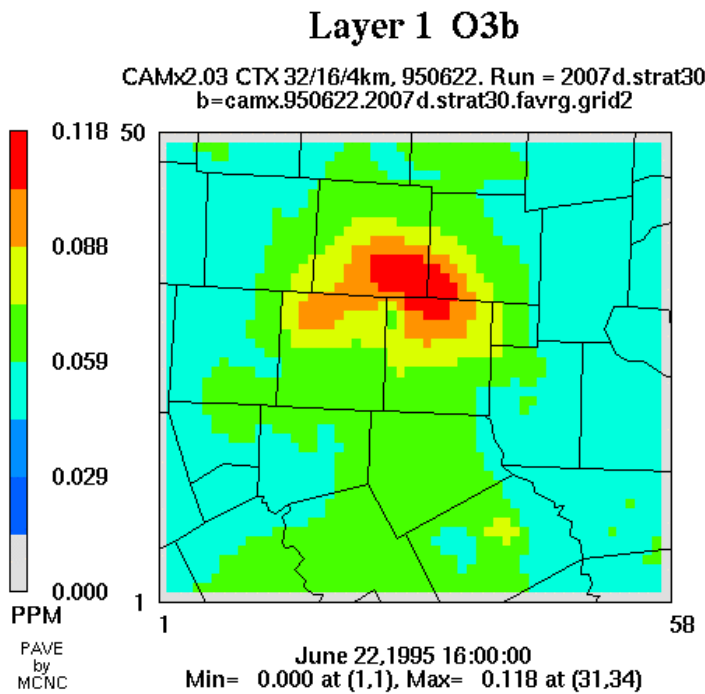


Figure 7-7 RT2, June 22, 16:00

Layer 1 O3a

CAMx2.03 CTX 32/16/4km, 950622. Run = 2007d.strat30.rt2  
a=camx.950622.2007d.strat30.rt2.favrg.grid2

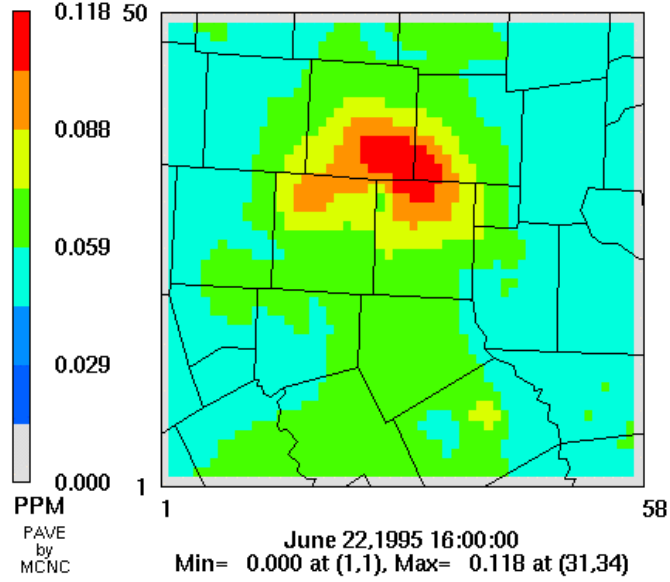


Figure 7-8 Base Case June 22, 19:00

Layer 1 O3b

CAMx2.03 CTX 32/16/4km, 950622. Run = 2007d.strat30  
b=camx.950622.2007d.strat30.favrg.grid2

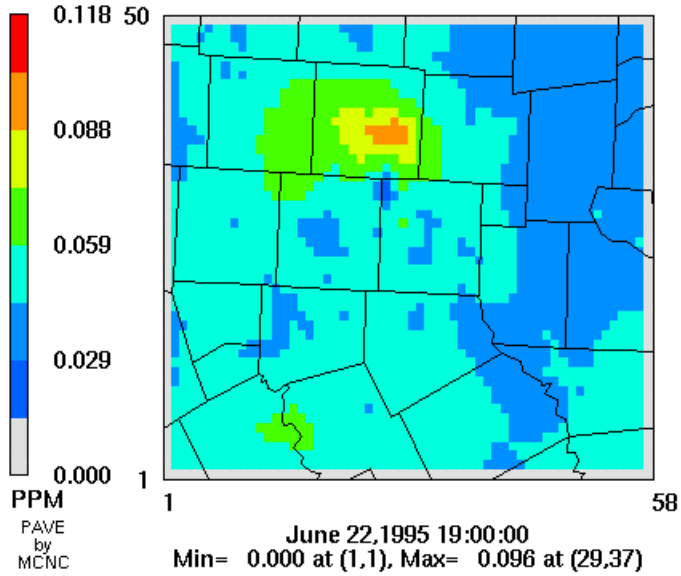


Figure 7-9 RT2, June 22 19:00

### Layer 1 O3a

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a=camx.950622.2007d.strat30.rt2.favrg.grid2

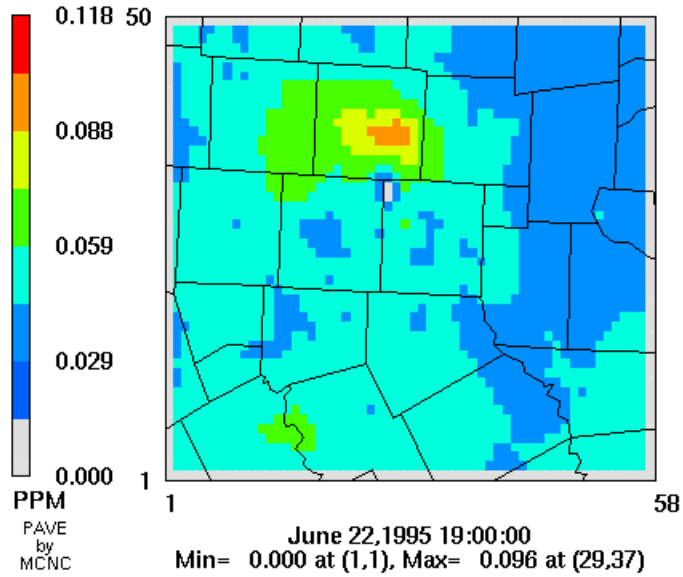
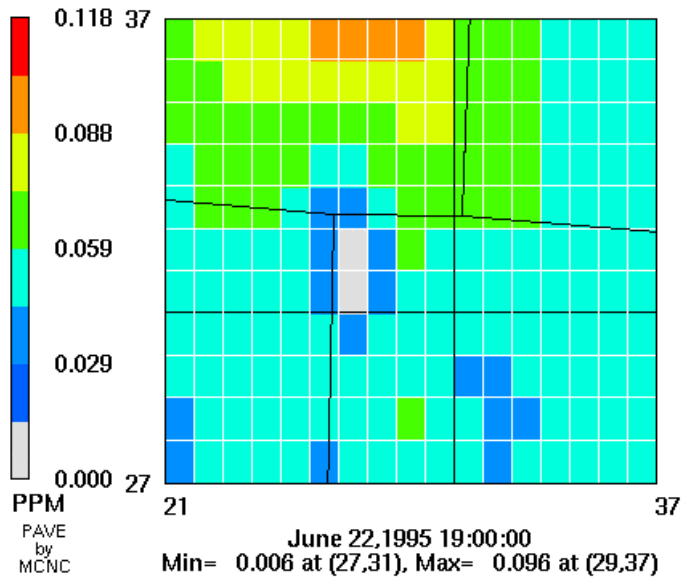


Figure 7-10 RT2 June 22, 19:00, Close-up

### Layer 1 O3a

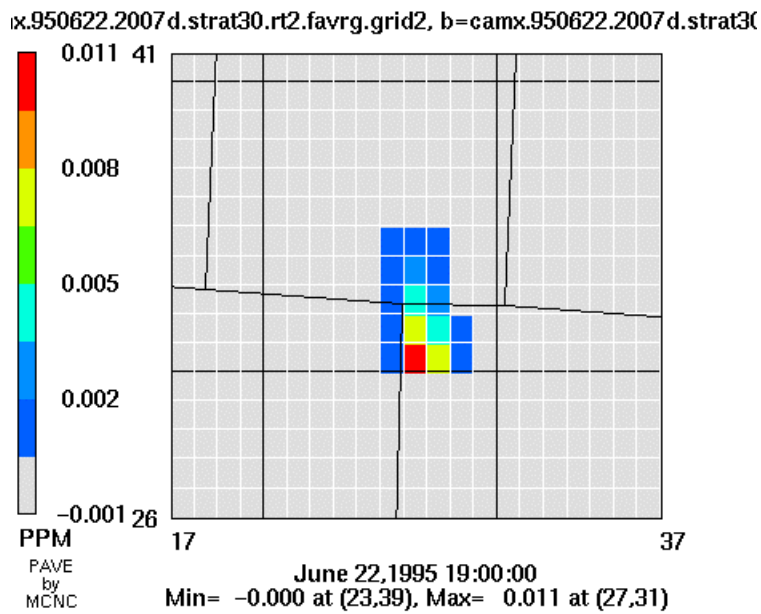
CAMx2.03 CTX 32/16/4km, 950622. Run = 2007d.strat30.rt2  
a=camx.950622.2007d.strat30.rt2.favrg.grid2



**Table 7-7 Estimated Ozone Levels Near DFW with Reverse Thrust at 19:00**

Grid Cell		O <sub>3</sub> (ppb)
x	y	
26	30	46
27	30	32
28	30	51
26	31	42
27	31	6
28	31	34
26	32	36
27	32	12
28	32	43
26	33	43
27	33	33
28	33	56

**Figure 7-11 Ozone Difference, Close-up  
Layer 1 O3b-O3a**



**Table 7-8 Difference in O<sub>3</sub> resulting from reverse thrust**

Grid Cell		O <sub>3</sub> (RT)-O <sub>3</sub> (base) (ppb)
x	y	
26	31	-1
27	31	-11
28	31	-7
29	31	-1
26	32	-1
27	32	-7
28	32	-5
29	32	-1
26	33	-1
27	33	-4
28	33	-2
26	34	-1
27	34	-2
28	34	-1
26	35	-1
27	35	-1
28	35	-1

**Figure 7-12 RT2, Nitrogen Dioxide**

**Layer 1 NO<sub>2</sub>a**

CAMx2.03 CTX 32/16/4km, 950622. Run = 2007 d.strat30.rt2  
a=camx.950622.2007 d.strat30.rt2.favrg.grid2

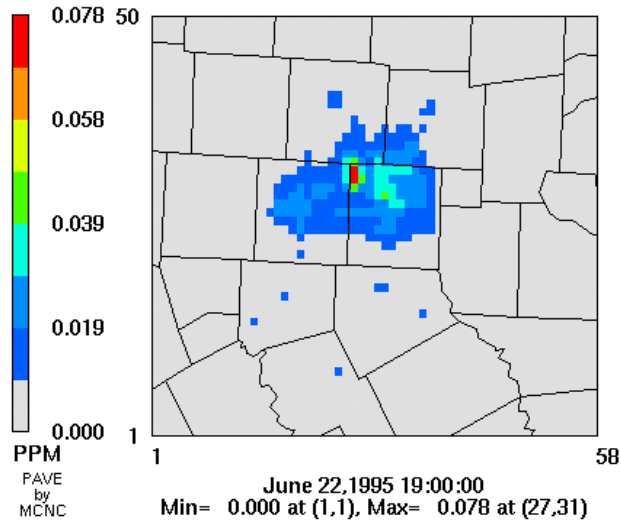


Figure 7-13 RT2, Nitrogen Dioxide, Close-Up

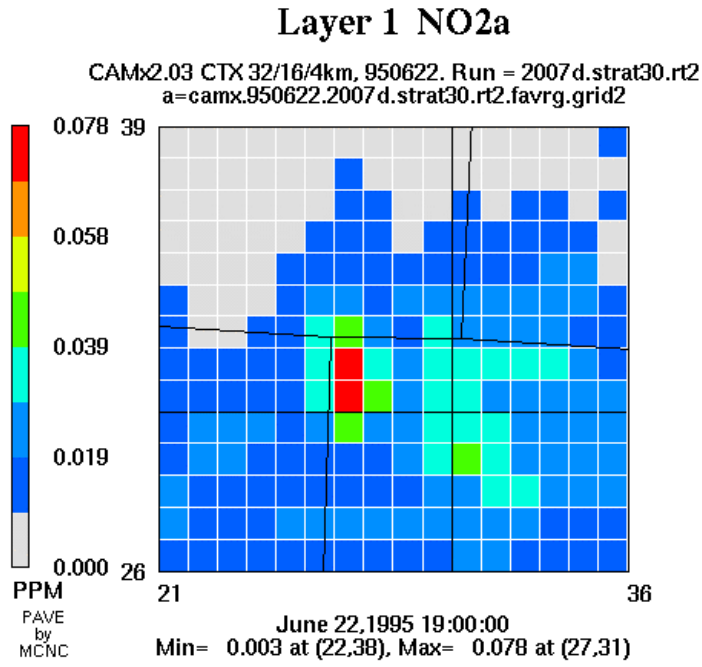
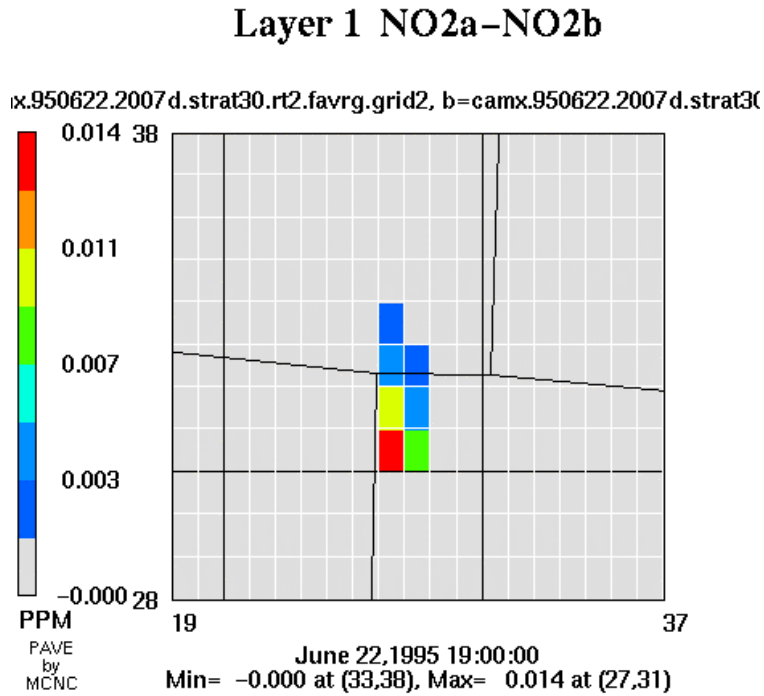


Figure 7-14 NO<sub>2</sub> Difference



**Table 7-9 NO<sub>2</sub> Levels Near DFW Airport**

Grid Cell		NO <sub>2(RT)</sub> (ppb)	NO <sub>2(RT)</sub> -NO <sub>2(base)</sub> (ppb)
x	y		
27	31	78	+14
28	31	45	+8
27	32	71	+10
28	32	37	+5
27	33	46	+5
28	33	24	+2
27	34	26	+2

#### **7.4 DISCUSSION OF NO<sub>x</sub> SCAVENGING**

Normally, nitric oxide (NO) quickly reacts with ozone to produce nitrogen dioxide (NO<sub>2</sub>) and molecular oxygen. In the case of DFW Airport, this process is clearly evident in the evening, as the concentration of O<sub>3</sub> is sharply reduced and NO<sub>2</sub> is sharply increased. NO<sub>2</sub> also accumulates during the evening, because sunlight is needed for photolysis, as shown by Formula 7-1. If photolysis does not occur, ozone formation is limited.

Although emissions from reverse thrust were found to decrease ozone levels near the airport, overall it is still desirable to reduce NO<sub>x</sub>. Additional NO<sub>x</sub> emitted can increase ozone levels downwind from the airport. NO<sub>x</sub> itself is an irritant and there is an EPA standard for nitrogen dioxide. For NO<sub>2</sub>, the NAAQS limit is an annual average of less than 55 ppb. High concentrations of NO<sub>x</sub> can result in discoloration and reduction in strength of fabrics. NO<sub>2</sub> is more toxic than NO and can also be the source of secondary air pollutants (Janssen, 1986). During the evening, NO<sub>2</sub> reacts with hydroxyl radicals to form nitric acid (HNO<sub>3</sub>), which can cause corrosion of metal. High concentrations of NO<sub>2</sub> can also reduce crop yield and cause respiratory problems (Wark, Warner, and Davis, 1998). In Texas, the NO<sub>2</sub> standard has never been violated. For this model run, NO<sub>2</sub> levels were forecasted to be above 55 ppb for 3 hours of the day, because of the airport.

## 7.5 CONCLUSION

Although emissions from reverse thrust are forecasted to have a minimal impact on regional ozone levels, their localized impact on ozone levels and nitrogen dioxide is more significant. Near the airport, ozone levels are decreased, while NO<sub>2</sub> levels are elevated, as the result of NO<sub>x</sub> scavenging. Since emissions from reverse thrust are not currently considered, the on-airport contribution of NO<sub>x</sub> is underestimated by nearly 15%. Because of the resulting increase in NO<sub>2</sub> concentrations, airport personnel, passengers, and nearby residents may be significantly affected. DFW Airport handles 170,000 passengers daily and 42,000 people are employed at the airport (DFW Airport Board, 2001). The area of increased NO<sub>2</sub> due to reverse thrust is estimated to cover approximately 112 square kilometers or 44 square miles. With the aid of the North Central Texas Council of Governments GIS information, it is estimated that 60,000 people are affected by the increased NO<sub>2</sub> levels.

In this episode, the daily peak for the Dallas region is unaffected by reverse thrust. However, when the peak occurs near the airport or near CAMS70, reverse thrust could possibly have an effect. The airport may have caused a reduction in the 8-hour average of ozone measured at C70. Without the airport, C70 may have produced the highest 8-hour average for the region.

## CHAPTER 8. FEASIBILITY

This chapter looks at the legal and operational ramifications for restricting the use of reverse thrust. Elimination of power-backs and wheel braking characteristics during landing are assessed. Restrictions on reverse thrust in Europe are also discussed. Finally, strengthening of the current aircraft NO<sub>x</sub> standard is proposed by the author, which would require a “phaseout” of high NO<sub>x</sub> emitting aircraft engines.

### 8.1 PROHIBITION OF POWERBACKS

Prohibiting the use of thrust reverse for power-backing may be a more viable alternative. Currently, American Airlines is the only carrier who practices power-backing of aircraft away from boarding bridges. The practice of power-backing is not allowed at permitted airports. Factors which influence power-backing include terminal apron configuration and proximity to other aircraft. American Airlines is the largest MD-80 operator and the largest operator of rear-engined aircraft. DFW is American’s only hub where power-backing is practiced. It is not practiced at Chicago/O’Hare and Miami because of the terminal layout.

Continental Airlines practiced power-backing approximately ten years ago. The airline stopped the practice because it felt power-backing was “unprofessional”. (Moody, 2000). Sacramento Metropolitan Airport (SMF) prohibited power-backing in 1999 solely for emissions reduction purposes (Humphries, 2000). Tamara Moore, airport planner for ABIA, stated that abrasion of the terminal building occurring near American Airlines’ gates is likely the result of power-backing. Applying a high level of engine power close to the terminal building can be dangerous if debris is present.

If American ceases power-backing, extra ground equipment would be needed in some cases. Extra time will be required to connect and disconnect the towbar to the aircraft’s nose gear (Vance, 2000). If power-backing was prohibited in Austin, two additional aircraft tows would need to be purchased, at a cost of nearly \$100,000 apiece (Vance, 2000). However, the extra cost may be offset in terms of fuel savings. Manpower requirements would not be increased, as three people are needed to walk backwards with aircraft, regardless of the method used. At DFW,

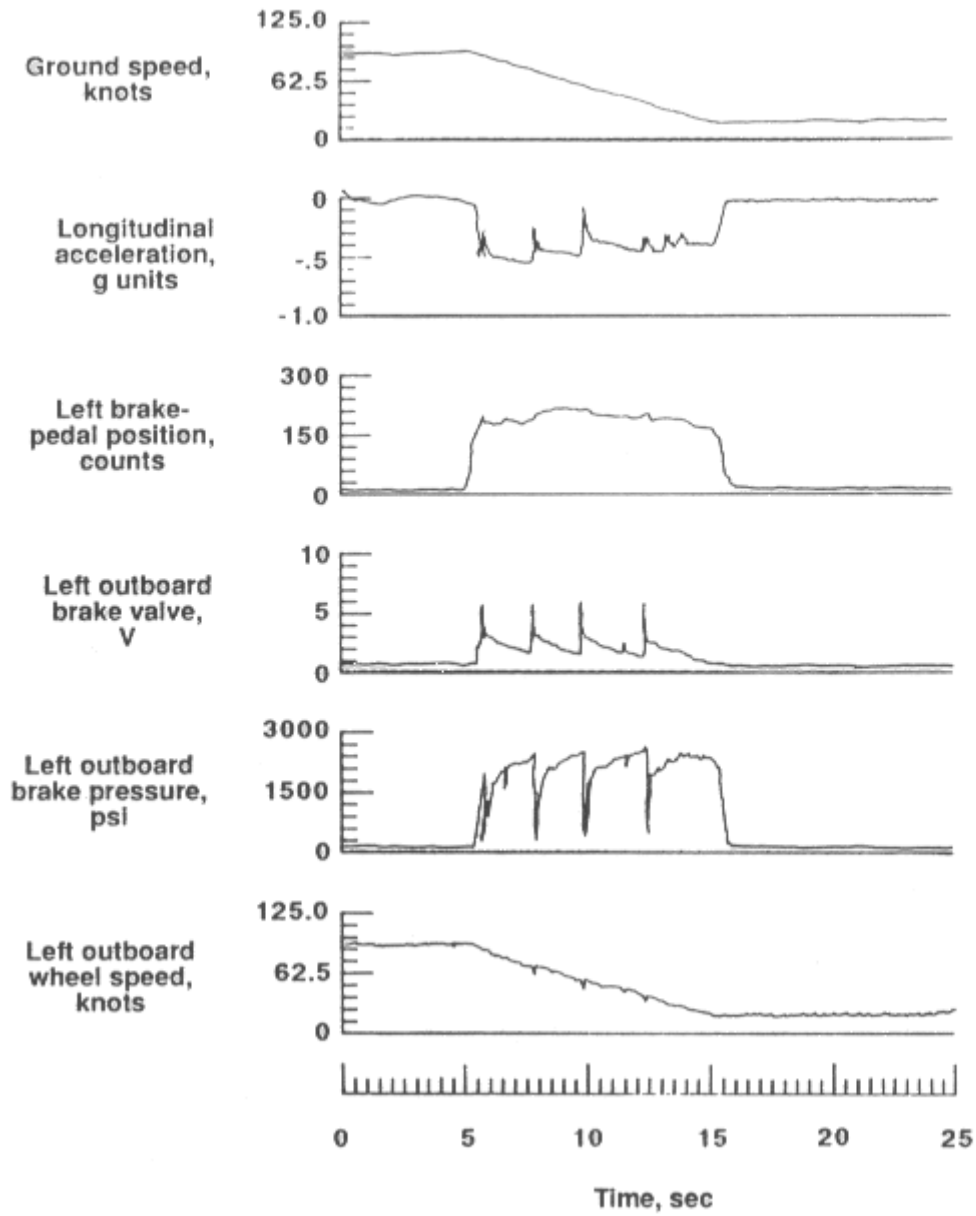
American Airlines operates 52 diesel aircraft tows (Hotard, 2000). With 64 gates, there is almost one for every gate. At DFW, few additional aircraft tows would be needed.

## **8.2 FEASIBILITY**

Thrust reversers are not an essential part of aircraft operations. The FAA does not require thrust reversers for aircraft certification or airworthiness. Thrust reversers are preferred by pilots for use on contaminated runways or for emergency stopping. Aircraft are fully capable of stopping with the use of their wheel brakes alone. In fact, wheel brakes by themselves can provide much more stopping power than the thrust reversers.

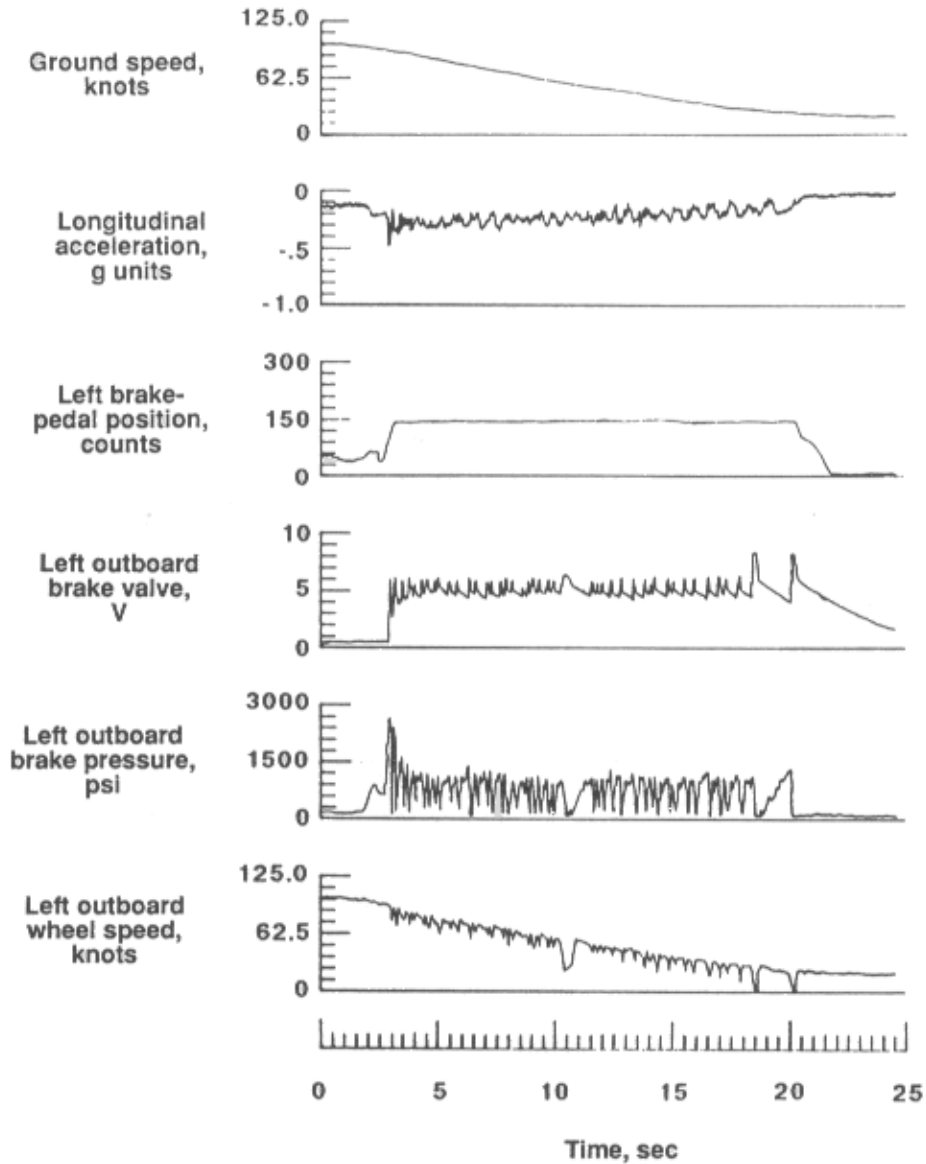
In Yager, Vogler, and Baldasare (1990), braking tests were conducted on Boeing 727 and B737 aircraft. Tests were conducted under a multitude of runway conditions, including dry, wet, icy, and snow-covered. When maximum anti-skid braking was applied on a dry runway for the B727, the aircraft decelerated from 90 knots to 20 knots in 10 seconds. This resulted in a deceleration of  $11.8 \text{ ft/sec}^2$  or  $0.37g$ . Normal aircraft deceleration during landing is  $4\text{-}5 \text{ ft/sec}^2$  (Horonjeff, 1992). A comparison between braking on dry and snow-covered runways is shown in Figures 8-1 and 8-2, courtesy of Yager, Vogler, and Baldasare (1990).

**Figure 8-1 Maximum Antiskid Braking for 727 Aircraft on a Dry Runway**



source: NASA Technical Paper 2917

**Figure 8-2 Maximum Anti-skid Braking for B727 Aircraft on a Snow-Covered Runway**



source: NASA Technical Paper 2917

As shown in Figure 8-2, stopping on a snow covered runway takes nearly twice as long as on a dry runway. On the snow covered runway, brakes are applied for 17 seconds, 7 seconds more than on a dry runway. This illustrates the importance of thrust reverser usage on contaminated runways.

Many European airports have restrictions on thrust reverse usage. Some U.S. airports have nighttime restrictions on thrust reverse usage. The primary motivation for these restrictions is to minimize the noise impact on the surrounding community. Takeoff and landing primarily affect people under the flight path; however, reverse thrust is noisiest along the sideline and in front of the aircraft. Table 8-1 shows details on European airports with restrictions on thrust reverse usage.

**Table 8-1 European Airports with Restrictions on Thrust Reverse Usage**

Airport	Restriction Type
Brussels National	nighttime
Frankfurt Main	nighttime
Madrid	Nighttime
Rome – Fiumicino	no times listed
Milan, Italy	Full restriction
Dusseldorf, Germany	nighttime
Oslo, Norway	nighttime
Berlin Tegel	Full
Berlin Tempelhof	Full
Hamburg	Full
Helsinki	Voluntary
Stuttgart	10 PM – 6 AM
Geneva	full
Manchester, UK	voluntary

Under normal conditions, since wheel brakes are more effective than thrust reversers, no reduction in airport runway capacity would be expected. Aircraft would be able to stop in the same distance using their wheel brakes alone. They would be able to use the same runway exits, therefore resulting in the same runway occupancy times. European airports such as Munich and Zurich, who also have full restrictions on thrust reverse usage, have reported no change in the average length aircraft landing rolls.

In general, a restriction on reverse thrust usage during landing would not be advisable on runways of less than 8,000 feet. On short runways, there is less margin for error and pilots need to have all methods of braking available if needed. Depending on weather conditions and runway slope, most jet aircraft require between 5,000 and 7,000 feet of runway during landing. As a result, most high-speed runway exits are typically located in this area (Horonjeff, 1992).

All of the European airports shown in Table 8-1 with restrictions on thrust reverse have runways longer than 8,000 feet. Both of Munich's runways are 13,000 feet, while DFW's landing runways are 11,400 feet and 9,000 feet. ABIA's runways are 12,250 feet and 9,000 feet.

### 8.3 OTHER CONSIDERATIONS

Several sources have suggested that the current aircraft emissions methodology may overestimate aircraft NO<sub>x</sub> emissions (Yamartino and Spitzak, 1994, Ogbeide, 2001). The methodology assumes that all aircraft take-off at full power (100%), which rarely occurs. The takeoff throttle setting is determined by the onboard computer and typically ranges between 75 and 90%. Twin-engine aircraft are generally overpowered so that in case of engine failure, the remaining engine has enough power to ensure a safe climbout. Airline procedures usually direct pilots to avoid using full power during takeoff, unless necessary, to reduce wear and tear on the engines. Using derated takeoff power enables longer durations between scheduled engine maintenance. Aircraft noise is also directly related with power-setting and most airports have noise abatement procedures in effect. Full power is used only during unusual circumstances, such as departing on a short runway or with a heavy load.

Since the majority of aircraft emissions are generated during takeoff and climbout, there is a high probability that aircraft NO<sub>x</sub> emissions are overestimated. During takeoff, using the 85% power setting and an 80% power setting during climbout to compute emissions instead of the current power settings would result in an estimation of 10% less NO<sub>x</sub>. This more realistic and would make the emissions produced from reverse thrust even more significant. (Yamartino and Spitzak, 1994).

Currently, all aircraft engines are able to meet the ICAO NO<sub>x</sub> standards. Even though stronger standards were adopted in 1997, new engines pass the revised standard with ease, while all older engines are still able to meet the revised standard, as shown in Figure 2-3 and 8-2. Another method of NO<sub>x</sub> emissions reduction for aircraft would be strengthening the standard an additional 20% to the following:

$$D_p/F_{00} = 24 + 1.2\pi_{00} \quad (8-1)$$

where:

$D_p$  = total mass of pollutant emitted during LTO

$F_{00}$  = max thrust per engine

$\pi_{00}$  = engine pressure ratio

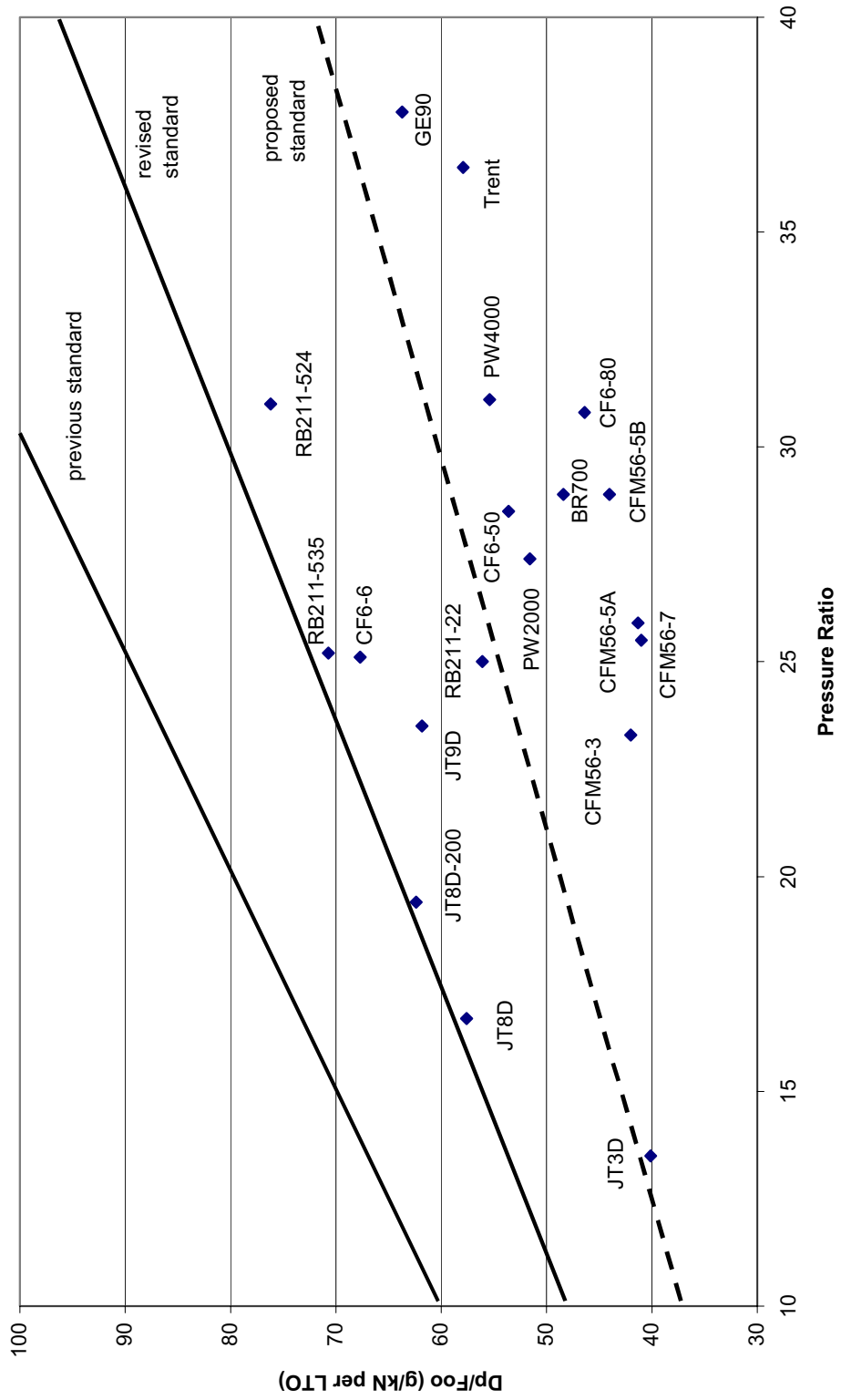
Figure 8-3 shows how the proposed standard compares with the previous standards. The proposed standard would require retirement or re-engining of aircraft with JT8, RB211, JT3, JT9, and CF6-6 engines, as those engines would not meet the standard. The affected aircraft would include the MD-80, B727, B737-200, L-1011, DC-8, B707, DC-10-10. Some models of the B747, B757, and B767 would be affected. The first group of aircraft are approaching 20 years old or older. Airlines have begun retiring the majority of those aircraft. In the case of DFW Airport, re-engining those aircraft with modern, lower-polluting engines could reduce the aircraft contribution of NO<sub>x</sub> by 10-15%.

#### **8.4 CONCLUSION**

Restricting the use of reverse thrust, during landing and power-backing, has potential as an emissions reduction strategy. Aircraft are capable of stopping using their brakes alone, under normal conditions. Additionally many airports around the world prohibit the use of thrust reversers. However, implementing emissions control measures for airports and aircraft is very difficult. Any mandatory restriction on thrust reverse would prompt immediate action by the Air Transport Association. The author anticipates that future disputes between environmental agencies and the airline industry will be dictated by the politics and the financial well-being of the airlines involved.

Figure 8-3 Proposed NOx standar

EPR vs Dp/Foo (NOx)



## CHAPTER 9. CONCLUDING REMARKS

### 9.1 OVERALL CONCLUSIONS

As previously discussed, reverse thrust is not currently included in aircraft emissions computations. This research analyzed factors which influence thrust reverse usage, quantified the associated NO<sub>x</sub> emissions at several major Texas airports, and evaluated the impact on local air quality for the Dallas region.

Reverse thrust is routinely used during landing as a braking aid and occasionally to powerback aircraft away from boarding gates. Factors found to influence thrust reverser usage during landing include thrust reverser type, aircraft type, airline, and runway exit configuration. From Chapter 5, The average duration of thrust reverse usage during landing at ABIA was found to be 16.0 seconds and estimated to be 15.4 seconds at DFW. For power-backing, reverse thrust usage was found to be 43.8 seconds.

Reverse thrust was found to have the largest impact at DFW Airport. This is because of the sheer number of aircraft operations and the practice of power-backing by American Airlines. From Chapter 7, reverse thrust was found to increase DFW Airport's on-airport NO<sub>x</sub> emissions by 15%. Because emissions from reverse thrust are a small fraction of regional NO<sub>x</sub> emissions, they are forecasted to have a minimal impact regional ozone levels. Their localized impact on ozone and nitrogen dioxide is more pronounced because of the significant concentration of additional nitric oxide produced. In this episode, the daily peak for ozone for the Dallas region is unaffected by reverse thrust. However, when the peak occurs near the airport or near CAMS70, reverse thrust could possibly have an effect. During ozone season 2001, CAMS70 recorded the highest frequency of 8-hour ozone standard violations. The airport NO<sub>x</sub> emissions may have in fact caused a reduction in the 8-hour average measured at CAMS70. Without the airport, CAMS70 may have produced the highest 8-hour average for the region.

As a result of NO<sub>x</sub> scavenging, ozone levels were found to be decreased in the vicinity of the airport. Including emissions from reverse thrust resulted in an even greater decrease of ozone levels near the airport. When NO<sub>x</sub> scavenging occurs, ozone reacts with NO to form NO<sub>2</sub>. Elevated levels of NO<sub>2</sub> were found to occur near the airport. The peak NO<sub>2</sub> for the Dallas region of 78 ppb occurs at the airport, where including reverse thrust results in a 14 ppb increase over the basecase. Airport personnel, passengers, and nearby residents may be significantly affected

by the increased NO<sub>2</sub> levels. DFW Airport handles 170,000 passengers daily and approximately 42,000 people are employed at the airport. (DFW Airport Board, 2001). The area affected by elevated levels of NO<sub>2</sub> attributed to reverse thrust covers approximately 112 square kilometers and it is estimated that 60,000 nearby residents may be affected.

Aircraft are capable of stopping during landing using their wheel brakes alone. Thrust reversers are primarily needed to aid in deceleration when landing during inclement weather, when wheel-braking power is diminished. Airlines instruct pilots to use thrust reversers during every landing, for added safety. There are many airports around the world which prohibit the use of thrust reversers. Although these restrictions are primarily for noise mitigation, there are also emissions benefits, as shown by Chapter 8.

As discussed in Chapter 8, a proposal was passed by TNRCC which required gradual conversion to all-electric GSE by 2005. This proposal was approved by TNRCC and became law in April 2000. It proposed to reduce GSE emissions by 90% or 9.54 tons per day. This law was challenged with a lawsuit filed by the ATA, who contended that the FAA bars regulation of aircraft operations. TNRCC argued that although it may lack jurisdiction over aircraft, it does have the right to regulate ground activity at airports. The EPA and the FAA also disagreed over the Dallas GSE issue. The FAA believed that regulating GSE at DFW would hamper aircraft operations, which would have been a contradiction of the Air Deregulation Act.

A settlement was reached in the ATA lawsuit during summer 2001 (TNRCC, 2001). The airlines agreed to a voluntary 75% reduction in GSE emissions by 2005. Given the legal implications demonstrated by this case, a mandatory restriction on reverse thrust would not be feasible. Pilots need to have reverse thrust available if necessary, particularly during emergencies or inclement weather. The ideal solution would be implementing a voluntary restriction when ozone and NO<sub>2</sub> formation is projected to be a problem.

Restricting the use of reverse thrust is an emissions reduction strategy which is easy to implement. Since restricting the use of reverse thrust does not require a costly capital investment, it has a very low cost per ton benefit. In lieu of mandating emissions reduction from GSE at DFW, airlines could be given a NO<sub>x</sub> emissions budget for their entire scope of operations. If their budget is exceeded, airlines could be charged a nominal fee for the amount emitted over the allowable quantity. The fee could be set according to the industry average cost of reducing NO<sub>x</sub>,

currently estimated at \$10,000 per ton. Emissions reduction could then be achieved by the airlines using a variety or combination of measures.

As discussed in Rice and Walton (2000), emissions surcharges at Zurich are minimal, compared with the overall aircraft operating cost. For American Airlines, emissions from reverse thrust are estimated to produce approximately 275 tons per year of NO<sub>x</sub>. A 75% reduction in GSE NO<sub>x</sub> for American Airlines at DFW would be 3.05 tons per day, which is equivalent to 1068 tons per year. At an arbitrary reduction cost of \$10,000 per ton, the GSE reduction amounts to a total of \$10.7 million per year. Eliminating reverse thrust would reduce the necessary amount of GSE reduction needed and could potentially save American \$2.75 million per year, if emissions budgets were implemented.

## **9.2 RESEARCH CONTRIBUTIONS**

This dissertation is an attempt to quantify NO<sub>x</sub> emissions associated with reverse thrust. In doing so, the impact of aviation-related activities on regional air quality was also evaluated. In the area of air transportation, this research provides an analysis of the characteristics which influence thrust reverse usage. Although efforts have been made to quantify the characteristics which influence aircraft landing distance, thrust reverse usage has not been comprehensively assessed. This study evaluated thrust reverse usage for a multitude of aircraft and airlines, coupled with the effect of runway exit type and landing direction, with a detailed statistical analysis.

Airports and their effect on air quality is becoming an increasingly important topic in the realm of transportation. Previously, the EPA has aggressively addressed automobile emissions. Airports have received little attention until recently. As automobiles and airport GSE become cleaner, the majority of NO<sub>x</sub> associated with aviation-related activities will be produced by aircraft engines. No major NO<sub>x</sub> emissions reduction measures for aircraft have been proposed. Restricting the use of reverse thrust is one of the only emissions reduction strategies aimed specifically at reducing aircraft NO<sub>x</sub>.

Beyond the year 2007, the proportion of regional NO<sub>x</sub> associated with aircraft will continue to grow as the number of air passengers increases and as more low-emitting motor vehicles (LEV) are introduced. The current ICAO NO<sub>x</sub> emissions standards have been designed around engines currently in production. All aircraft engines are able to pass even the revised

standard. In order to keep the relative aircraft proportion of NO<sub>x</sub> from increasing, a stricter NO<sub>x</sub> standard, similar to the one proposed by the author, is needed. As discussed in Section 8.3, revising the current ICAO NO<sub>x</sub> standard an additional 20% is shown in Equation 9-1.

$$D_p/F_{00} = 24 + 1.2\pi_{00} \quad (9-1)$$

where:

$D_p$  = total mass of pollutant emitted during LTO

$F_{00}$  = max thrust per engine

$\pi_{00}$  = engine pressure ratio

### 9.3 FUTURE RESEARCH

According to the EPA Office of Transportation and Air Quality, the TIMs currently used for computation of aircraft emissions were developed in the early 1970s. Although no formal record exists, they were measured at several major airports (Petche, 2001). At that time, the only commercial jet aircraft in service were the 707, DC-8, DC-9, 727 and 737. Deliveries of the 747 and DC-10 were just beginning. Today's aircraft perform much better than the aircraft of the past. They accelerate faster during takeoff and they climb faster during climbout. It is possible that the TIMs used may be too large. More measurement and simulation are needed to validate the TIMs. Additionally, it has been suggested that the current methodology may overestimate aircraft emissions. The methodology assumes that aircraft always takeoff at full power. In reality, this rarely occurs. Pilots typically use a cutback power setting to reduce wear and tear on the engines. If takeoff emissions are overestimated, it is possible that emissions from reverse thrust are even more significant.

When thrust reversers are deployed, the directivity of the noise radiating from the engine is different. During forward thrust, the noisiest area is along a path which is at an angle of 135° from the direction of motion. For thrust reverse, the noisiest place is along the sideline, perpendicular to the direction of the aircraft motion. The Integrated Noise Model (INM) models thrust reverse at 60% power, without changing the directivity of the noise. Noise associated with

reverse thrust needs to be more accurately modeled. Noise measurements need to be taken during landing along a runway to establish a thrust reverse noise footprint.

The impact of thrust reverse on local air quality needs to be should at other busy airports in non-attainment areas. DFW is the busiest airport where power-backing is practiced; therefore, emissions from reverse thrust will be most significant in the Dallas area. Atlanta, Chicago/O'Hare, DFW, and LAX are the world's four busiest airports. Power-backing is practiced in Atlanta by only American Airlines. Since Delta is the dominant carrier in Atlanta, emissions from power-backing may not be as significant.

Airport GSE also produce a significant quantity of NO<sub>x</sub> over a small area. However, as discussed by Chapter 8, the estimated NO<sub>x</sub> emissions associated with GSE at DFW are thought to have been overestimated. The current GSE contribution of NO<sub>x</sub> was estimated to be nearly equal to the amount generated by aircraft. The effect of GSE on air quality is projected to be similar to the effect of reverse thrust. The 2007 CAMx model run assumed that the GSE electrification proposal would remain upheld, and that a 90% reduction of NO<sub>x</sub> from GSE would occur. With the recent settlement between the ATA and TNRCC, the airport's contribution of regional NO<sub>x</sub> may be much larger. Depending on the amount of voluntary NO<sub>x</sub> reduction achieved by the airlines, emissions from GSE may or may not have a significant impact on regional ozone levels by 2007. Further air quality simulation needs to be performed to show the effect of GSE in Dallas before deciding whether to pursue additional emissions reduction strategies.



## REFERENCES

- Airports Council International, North American Traffic Statistics, [www.aci-na.org/new\\_website/frame\\_stats.html](http://www.aci-na.org/new_website/frame_stats.html), 2000.
- Baughcum, Steven L., Terrance G. Tritz, Stephen Henderson, and David C. Pickett. "Scheduled Civil Aircraft Emission Inventories for 1992", NASA Contractor Report 4700, NASA Langley Research Center, April 1996.
- Berg, Jane. Flight Operations, Northwest Airlines. Phone Interview, September 2000.
- Boeing Commerical Airplanes. Boeing Noise Regulation Database, [www.boeing.com/assocproducts/noise/airports.html](http://www.boeing.com/assocproducts/noise/airports.html), 2000.
- Borowiec, Jeffrey D., Teresa Qu, and Charles E. Bell. "1996, 1999, and 2007 Airport Emissions Inventory", Technical Note 402011-8, Texas Transportation Institute, March 2000.
- Bowlby, William and Roger L. Wayson. "Use of Microcomputers to Perform Airport Emission Inventories" Journal of Transportation Engineering, Vol. 116, No. 3, May/June 1990, pp. 328-337.
- Boyle, Karleen A. "Evaluating Particulate Emissions from Jet Engines: Analysis of Chemical and Physical Characteristics and Potential Impacts on Coastal Environments and Human Health" Transportation Research Record 1517, 1996, pp. 1-9.
- Cooke, Gregg, EPA Regional Administrator. Letter to Robert Huston, TNRCC Chairman. June 23, 2000.
- CSSI, Inc. "EDMS Reference Manual Version 3.11," April 1997.
- Dallas/Ft. Worth Airport Board. DFW International Airport., [www.dfwairport.com](http://www.dfwairport.com), July 2001.
- Draper, Julie, Mariano Pernigotti, and Diane Liang. "Air Quality Procedures for Civilian Airports and Air Force Bases", FAA Report AEE-97-03, April 1997.
- Dykeman, Paul, Deputy Director, FAA Office of Environment and Energy. Letter to Donald Zinger, Assistant Director, EPA Office of Transportation and Air Quality. August 24, 2000.
- Energy and Environmental Analysis, Inc. "Technical Data to Support FAA's Advisory Circular on Reducing Emissions from Commercial Aviation", September 1995.
- Fabian, Lawrence J. "Rationalizing Airport Ground Access" Tranportation Quarterly, Vol. 47, No. 4, October 1993, pp.473-482.

- Federal Aviation Administration. Terminal Area Forecasts. <http://www.apo.data.faa.gov>, 2000.
- Fleuti, Emmanuel. Head of Air Quality Services. Zurich International Airport. Phone Interview. April 2000.
- General Electric. GE Aircraft Engines. [www.geae.com](http://www.geae.com), 2000.
- Gillani, Noor V., James F. Meagher, Ralph J. Valente, et al. "Relative Production of Ozone and Nitrate in Urban and Rural Power Plant Plumes" Journal of Geophysical Research, Vol 103, No D17, pp. 22593-22615, 1998.
- Hawthorn, Gary. "Transportation Provisions in the Clean Air Act Amendments of 1990." ITE Journal, April 1991, pp.17-24.
- Higgins, Thomas J. "California Airports: Ground Access Vehicle Trips, Emissions and Emission Reduction Strategies", in Proceedings of the 23<sup>rd</sup> International Air Transportation Conference, 1994, pp. 102-123.
- Horonjeff, Robert and Francis X. McKelvey. Planning and Design of Airports, 4<sup>th</sup> ed, New York: McGraw-Hill, 1992.
- Hotard, John. Corporate Communications Manager, American Airlines. Phone Interview, May 2000.
- Humphries, Jim. Air Quality Coordinator, Sacramento International Airport. Phone Interview. March, 2000.
- International Civil Aviation Organization, "Environmental Protection: Annex 16, Volume II - Aircraft Engine Emissions," November 1993.
- International Civil Aviation Organization, "Aviation Emissions Databank", Document. 9646-AN/943, 1995.
- Jamieson, J.B. "Twenty-First Century Aero-Engine Design: The Environmental Factor" Journal of Aerospace Engineering Part G, 1990, p.119-134.
- Janssen, L. H. J. M. "Mixing of Ambient Air in a Plume and Its Effects on the Oxidation of NO" Atmospheric Environment, Vol 20, No 12, pp. 2347-2357, 1986.
- Kanzler, Peter. Operations Manager, Munich International Airport. Phone Interview, March 2000.
- Lohr, Sharon L. Sampling: Design and Analysis. Pacific Grove, CA: Brooks/Cole Publishing, 1999.

- Luria, Menachem, Ralph J. Valente, Roger L. Tanner, et al. "The Evolution of Photochemical Smog in a Power Plant Plume" Atmospheric Environment Vol 33, pp. 3023-3036, 1999.
- Montgomery, Douglas C. Design and Analysis of Experiments, 4<sup>th</sup> Ed. New York: Wiley & Sons, 1997.
- Moody, Chris. Hub Operations, Continental Airlines. Phone Interview. October 2000.
- Morrell, Peter and Cherie H.-Y. Liu. "Social Costs of Aircraft Noise and Engine Emissions" Transportation Research Record 1703, pp.31-38.
- Moussiopoulos, N., P. Sahm, et al. "Analysis of the Impact of the New Athens Airport on Urban Air Quality With Contemporary Air Pollution Models" International Journal of Environment and Pollution, Vol. 8, Nos. 3-6, 1997.
- Moxon, Julian. "Environmental Effort" Flight International, July 24, 2000. p.116-126.
- National Climatic Data Center. NCDC Archived Weather Data. <http://lwf.ncdc.noaa.gov/oa/ncdc.html>, 2000.
- North Central Texas Council of Governments. DFWMaps.com, [www.dfwmaps.com](http://www.dfwmaps.com).
- Ogbeide, Peter. Mobile Source Division, Texas Natural Resource Conservation Commission. Interview. January 2001.
- Pearl, Ira. Delta Airlines Environmental Manager. Phone Interview, February 2000.
- Perl, Anthony, Judith Patterson, and Marc Perez. "Pricing Aircraft Emissions at Lyon-Satloas Airport" Transportation Research D, Volume 2, Number 2, 1997. pp. 89-105.
- Petche, Ken. EPA Office of Transportation and Air Quality. Phone Interview. March 2001.
- Popp, Peter J., Gary A. Bishop, and Donald H. Stedman. "Method for Commercial Aircraft Nitric Oxide Emission Measurements" Environmental Science Technology 33, 1999, pp. 1542-1544.
- Pratt & Whitney Aircraft Engines. Pratt & Whitney. [www.pratt-whitney.com](http://www.pratt-whitney.com), March 2000.
- Rice, Colin. "Modeling the Emissions Impact of a Vehicle Buyback Program for Austin," Working Paper, 1999.
- Rice, Colin and C. Michael Walton, "Evaluating Operating Strategies and Transportation Control Measures Which Reduce Air Pollution Emissions at Airports", Southwest University Transportation Center Report 473700, August 2000.

- Rothstein, Marcus. Vice-President of Engineering. Pratt & Whitney Aircraft Engines, Phone Interview, April 2000.
- Seinfeld, John H. and Spyros N. Pandis. Atmospheric Chemistry and Physics. New York: John Wiley & Sons, 1998.
- Skinn, Donald, Daniel O. Tipps, and John Rustenburg. “Statistical Loads Data for Boeing 737-400 Aircraft in Commercial Aircraft Operations”, FAA Report AR/98-28, July 1998.
- Skinn, Donald, Daniel O. Tipps, and John Rustenburg. “Statistical Loads Data for MD 82/83 Aircraft in Commercial Aircraft Operations,” FAA Report AR/98-65, February 1999.
- Texas Natural Resource Conservation Commission. “Agreed Order” Docket Number 2000-1149-SIP, 2001.
- Texas Natural Resource Conservation Commission. Air Quality Modeling and Data Analysis, [www.tnrcc.state.tx.us/air/aqp/airmodeling.html](http://www.tnrcc.state.tx.us/air/aqp/airmodeling.html), September 2001.
- Texas Natural Resource Conservation Commission, “Dallas/Ft. Worth Attainment Demonstration”, 2000.
- Texas Natural Resource Conservation Commission, “GSE – Final Rule”, Rule Log 1999-055E-114-A1, 1999.
- Texas Natural Resource Conservation Commission. Ozone in Texas, [www.tnrcc.state.tx.us/ozone.html](http://www.tnrcc.state.tx.us/ozone.html), May 2001.
- TransWorld Airlines, Flight Operations Office, Phone Interview, October 2000.
- URS Greiner. “Dallas/Ft. Worth International Airport: Inventory of Air Emissions”, July 1998.
- USAirways, Corporate Communications Office, Phone Interview, October 2000.
- United States Environmental Protection Agency. “EPA’s Nonroad Engine Emissions Control Programs”, Report EPA420-F-99-001, January 1999.
- United States Environmental Protection Agency. “Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft”, Report EPA 420-R-99-013, April 1999.
- United States Environmental Protection Agency. “Technical Support for Development of Airport Ground Support Equipment Emissions Reductions”, Report EPA420-R-99-007, May 1999.
- United States Environmental Protection Agency. Background on PAMS, [www.epa.gov/oar/oaqps/pams/general.html](http://www.epa.gov/oar/oaqps/pams/general.html), 2001.

- US Environmental Protection Agency, "Proposed Standards for Control of Air Pollution from Aircraft and Aircraft Engines", Federal Register, Volume 37, No. 239, December 12, 1972.
- US Environmental Protection Agency, "Final Rule: Emissions Standards and Test Procedures for Aircraft," Federal Register, Volume 38, No 136, July 17, 1973.
- US Environmental Protection Agency, "Final Rule: Supersonic Aircraft", Federal Register, Volume 41, No 159, August 16, 1976.
- US Environmental Protection Agency, "Final Rule: Extension of Compliance Date for Emission Standards Applicable to JT3D Engines", Federal Register, Volume 44, No. 218, November 6, 1979.
- US Environmental Protection Agency, "Final Rule: Control of Air Pollution from Aircraft and Aircraft Engines (Amendments)", Federal Register, Volume 47, No 251, December 30, 1982.
- US Environmental Protection Agency, "Final Rule: Control of Air Pollution from Aircraft and Aircraft Engines; Smoke Emissions Standard (Amendments)", Federal Register, Volume 48, No. 198, October 12, 1983.
- Vance, David. Station Manager, American Airlines, Austin, TX. Telephone Interview, May 2000.
- Wark, Kenneth, Cecil F. Warner, and Wayne T. Davis. Air Pollution: Its Origin and Control, 3<sup>rd</sup> ed, Menlo Park, CA: Addison Wesley Longman, 1998.
- Wayson, Roger L. and William Bowlby. "Airport Air Pollutant Inventories: Pitfalls and Tools." Transportation Research Record 1240, 1989, pp. 28-36.
- Wilkes, Jack M. Pilot, Alaska Airlines. Interview, May 2000.
- Woodmansey, B. Gordon and Judith Patterson. "New Methodology for Modeling Annual-Aircraft Emissions at Airports" Journal of Transportation Engineering, Vol 120., No 3, May/June 1994, pp. 339-357.
- Yager, Thomas J., William A. Vogler, and Paul Baldasare. "Evaluation of Two Transport Aircraft and Several Ground Test Vehicle Friction Measurements Obtained for Various Runway Surface Types and Conditions", NASA Technical Paper 2917, February 1990.
- Yamartino, R. and M. Spitzak "New Directions in Airport Air Quality Evaluation" Technical Paper AIAA-95-0444, American Institute of Aeronautics and Astronautics, 1994.
- Yetter, Jeffrey A. "Why do Airlines Want and Use Thrust Reversers?" NASA Technical Memorandum 109158, January 1995.

Zurich Airport Authority, "Aircraft Engine Emissions Charges at Zurich Airport", April 1997.