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RESTRICTING THE USE OF REVERSE THRUST AS AN EMISSIONS REDUCTION STRATEGY

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RESTRICTING THE USE OF REVERSE THRUST AS AN EMISSIONS REDUCTION STRATEGY

by

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Dedicated with love to the memory of my mother

Cecelia Ann Hawkins Rice,

without whom the foundation for this work

would not have been possible.

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AS AN EMISSIONS REDUCTION STRATEGY

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The University of Texas at Austin, 2001

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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.

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 dissertation 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. A policy analysis will also be performed, identifying the legal and safety ramifications resulting from a restriction on thrust reverse usage.

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1.0 INTRODUCTION

1.1 Problem Statement

Many sunbelt cities are currently exceeding or will soon exceed the EPA's revised National Ambient Air Quality Standards for ozone in the very near future. These cities are commonly located in volatile organic compound (VOC) saturation regions, where reductions in oxides of nitrogen (NOx) must be achieved in order to reduce ozone levels. Jet aircraft engines are a significant source of NOx at airports. Yet, proposed emissions reduction strategies target passenger automobiles and airport ground service equipment (GSE). At many airports, the future growth in NOx emissions from aircraft is estimated to offset any reduction achieved from GSE or passenger vehicles. With metropolitan areas seeking 45-75% reductions in total NOx emissions, NOx control strategies for aircraft are urgently needed.

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 NOx emissions (Rice and Walton, 2000). Therefore, it is likely that overall airport NOx 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 NOx in the future. This will create significant air quality impacts in the vicinity of the busiest airports.

Reverse thrust is not essential for aircraft operations. The Federal Aviation Administration does not require airplanes to have or use thrust reversers. Pilots prefer to use them as an added margin of safety, particularly on wet or icy runways. There are many airports around the world which prohibit or restrict the use of thrust reversers.

1.2 Research Objectives

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 NOx 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 NOx 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).

1.3 Methodological Framework

In order to assess the amount of emissions generated during reverse thrust, an additional phase of operation must be added to the current emissions computation methodology. This new phase will adequately simulate emissions by using a new time-in-mode (TIM) and appropriate emissions factor. A composite TIM for reverse thrust can be developed by monitoring the duration of reverse thrust usage by aircraft at airports. Reverse thrust application is easily discernible as the reverser is visibly deployed and there is a noticeable increase in engine power.

Two phases of data collection were implemented at Austin/Bergstrom International Airport (ABIA). For the first phase, a camcorder was situated in the grassy area behind American Airlines’ gates at ABIA to monitor power-backs. For the second phase, camcorders were placed near both runways in the area where reverse thrust is used during landing, approximately 5,000 feet from the landing end and between 400 and 800 feet from the runway centerline. The cameras provided a video feed for visual identification of aircraft. The audio collected by the cameras were used to determine the duration of thrust reverser usage. The camera will be patched into a VCR, which allowed as much as 8 hours between tape changes.

After the data collection is complete, analysis of variance will be performed to isolate the factors which influence thrust reverser usage. Factors thought to influence thrust reverser usage include aircraft type, airline, runway length, and runway exit configuration. Next, a TIM will be developed for reverse thrust usage during landing and power-backing. A power-setting for reverse thrust will be developed using available data from previous research. Emissions factors for aircraft engines are published for only four modes of operation, shown in Table 1-1.

Table 1-1 Assumed Aircraft Engine Power Settings by Mode of Operation

Phase	Engine Power Setting
Takeoff	100%
Climbout	85%
Approach	30%
Idle	7%

The relationship between power settings and aircraft emissions factors is estimated to be linear between each of the phases of operation (Baughcum et al, 1996). Once a power-setting for reverse thrust was established, NOx emissions factors were interpolated accordingly. This enabled computation of NOx produced during reverse thrust.

Emissions from reverse thrust are thought to have the most significant effect at Dallas/Ft. Worth International Airport (DFW). DFW is the only major hub airport where power-backing is practiced on a widescale basis. In 1999, DFW handled 867,000 aircraft operations. The EPA has given the Dallas/Ft. Worth and Houston/Galveston non-attainment regions until the year 2007 to achieve attainment for ozone. The year 1996 was chosen as the base year for Texas' State Implementation Plan emissions modeling. Emissions estimates of NOx were developed for selected Texas airports in non-attainment or near non-attainment areas for the years 1996 and 2007, based on historical traffic counts and future traffic forecasts.

After the reverse thrust emissions estimates were developed, the impact of reverse thrust on regional air quality was simulated with CAMx. The year 2007 is the deadline for the Houston and Dallas metropolitan areas to achieve attainment status for ozone. Emissions from reverse thrust will be most significant at that time and two runs were made with CAMx, with and without the effect of reverse thrust. Afterwards, the results were compared and the regional impacts on levels of ozone and nitrogen dioxide were evaluated.

Implementing a restriction on thrust reverse is undoubtedly a controversial topic. A policy analysis will be performed and the legal ramifications and safety considerations will be studied. Concluding remarks on the viability of restricting the use of reverse thrust as an emissions reduction strategy will be offered.

2.0 BACKGROUND

This chapter provides essential background information on environmental regulation as it pertains to air transportation. The first section discusses air quality regulation at airports from a historical perspective. The role of each of the regulatory agencies is discussed and the emissions standards and computation methodology are presented. The second section provides important background on aircraft engines and compares the amount of pollution generated by each. The third section discusses conformity and its importance for airport expansion projects. The fourth and fifth sections discuss development of aircraft emissions inventories and common aircraft emissions reduction strategies. The sixth section provides background on air pollution control for the Dallas/Ft. Worth area and focuses on the importance of NOx control measures for the airport. The final section proposes restricting the use of reverse thrust as an emissions reduction strategy for aircraft and provides pertinent information on the operation of thrust reversers.

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. The EPA justified adoption of aircraft emissions standards in 1973 by stating the following:

> “In judging the need for the regulations, the Administrator has determined (1) that the public health and welfare is endangered in several air quality control regions by violation of one or more of the NAAQS for carbon monoxide, hydrocarbons, nitrogen oxides, and photochemical oxidants, and that the public welfare is likely to be endangered by smoke emissions; (2) that airports and aircraft are now or are projected to be significant sources of emissions for carbon monoxide, hydrocarbons, and nitrogen oxides in some of the air quality control regions in which the NAAQS are being violated…
> (3) Accordingly, the Administrator has determined that emissions from aircraft and aircraft engines should be reduced to the extent practicable with present and developing technology.” (EPA, 1973)

The regulation of aircraft engine emissions has had an interesting history. 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	

ICAO began to study the environmental effects of aviation in 1969. In 1972, at the United Nations Conference on the Human Environment, ICAO stated its position as follows:

> “In fulfilling this role ICAO is conscious of the adverse environmental impact that may be related to aircraft activity and its responsibility and that of its member States to achieve maximum compatibility between the safe and orderly development of civil aviation and the quality of the human environment;”

In the beginning, ICAO focused on aircraft noise. The first noise standards were formally adopted by ICAO in 1973. 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.

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

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

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

Hydrocarbons

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

Carbon Monoxide

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

NOx

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

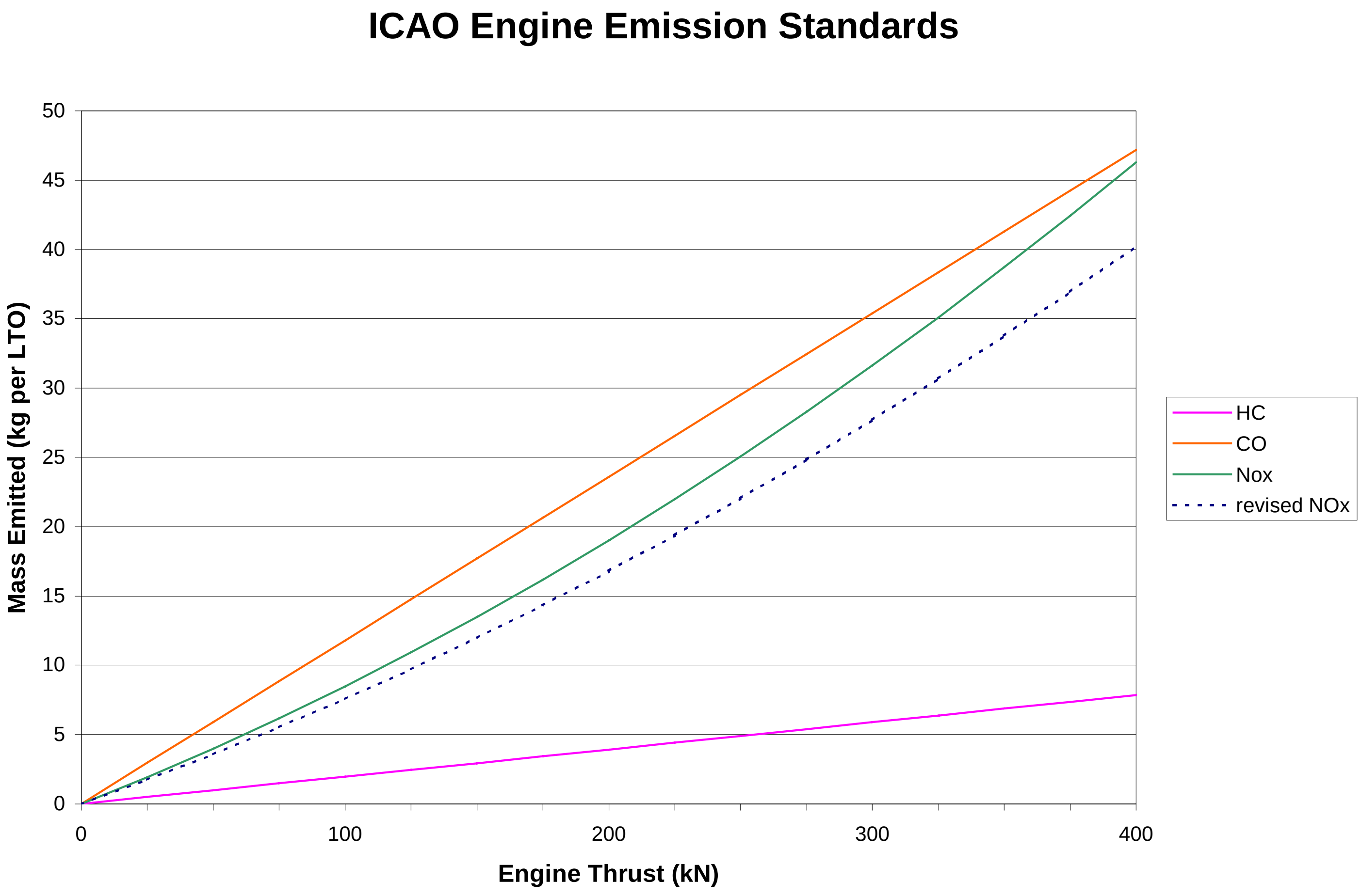
where:

D_p = mass of the gaseous pollutant emitted in grams per LTO
F_{oo} = total engine rated thrust output in kN
π_{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.

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

Figure 2-1


ICAO Engine Emission Standards
Mass Emitted (kg per LTO)
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
Engine Thrust (kN)
HC
CO
Nox
revised NOx

2.2 Aircraft Engines

Commercial jet aircraft engines are made by five groups: General Electric, Rolls Royce, Pratt and Whitney, CFM International, and International Aero Engines (IAE). CFM International is a consortium of Snecma of France and General Electric of the United States. IAE is a consortium consisting of Pratt and Whitney, Rolls Royce, Japanese Aero Engines, and MTU. Pratt and Whitney is U.S. based, Rolls Royce is based in the United Kingdom, while MTU is based in Germany. In the consortium, each company is responsible for a specific engine module. For example, in IAE, Pratt & Whitney is responsible for the combustor and turbine, while Rolls Royce is responsible for the compressor.

For first and second generation aircraft, the aircraft engine market was dominated by Pratt & Whitney. Pratt & Whitney was the only the producer of engines for the Boeing 707, 727, B737-100/200, Douglas DC-9, and McDonnell Douglas MD-80. Pratt & Whitney's JT8D is the most popular aircraft engine ever built. In the 1960s, Rolls Royce and General Electric did produce commercial aircraft engines, but they did not have a large market share. Rolls Royce and GE became popular in the 1970s, with the advent of widebodied aircraft and the need for high thrust, high-bypass turbofan engines.

Table 2-3 shows the most common jet aircraft engines in use today, their certification date, emissions indices for NOx, engine pressure ratio, and the quantity of NOx generated per LTO. Engine pressure ratio is defined as the ratio of the pressure difference induced to the engine airflow by the compressor. It can be a measure of the engine compressor's effectiveness. D_p/F_{00} is a measure used to show the "environmental efficiency" of an engine. It shows the quantity D_p of emissions of a pollutant (in grams) produced per unit of thrust (in kiloNewtons). To compute D_p/F_{00} for an engine, the total quantity of a pollutant emitted during a typical LTO is divided by the maximum thrust produced F_{00}. (ICAO, 1993)

Table 2-3 Common Aircraft Engines (ICAO, 1995)

engine	cert date	EI(Nox) at Takeoff (g/kg)	EPR	Dp/Foo (g/kN)	aircraft
JT3D	1958	12.4	13.5	40.1	B707, DC8
JT8D	1964	19.7	16.7	57.6	727, B737, DC9
JT9D	1969	39.4	23.5	61.8	B747,B767
CF6-6	1971	40.8	25.1	67.7	DC-10-10
CF6-50	1972	30.5	28.5	53.6	A300, DC-10, B747
RB211-22	1972	35.8	25	56.1	L1011
RB211-524	1977	50	31	76.2	B747,B767,L1011
JT8D-200	1980	25.2	19.4	62.4	MD-80
CF6-80	1982	29.2	30.8	46.4	A300, A310, B767, B747 MD-11
RB211-535	1983	47.7	25.2	70.7	B757
CFM56-3	1984	18.6	23.3	42	733,734,735
PW2000	1984	32.7	27.4	51.6	B757
PW4000	1986	36.1	31.1	55.4	B747,B767,A300, A310
CFM56-5A	1987	24.6	25.9	41.3	A320
V2500	1989	30.2	29	54.3	A320,MD90
CFM56-5C	1991	35	30	54.1	A340
CFM56-5B	1993	27	28.9	44	A320,A321
GE90	1995	49.7	37.8	63.7	B777
BR700	1996	24.9	28.9	48.4	B717
CFM56-7	1996	21.2	25.5	41	B737-NG
Trent	1997	37.8	36.5	57.9	B777

Figure 2-2 shows historical engine emissions indices for NOx during takeoff. A trend line is also displayed, which shows NOx emissions indices gradually increasing over time. Emissions indices are also a measure of engine environmental efficiency. They represent the amount of pollutant generated per unit of fuel burned. However, as an engine increases in efficiency, the amount of fuel burned per unit of thrust decreases. Therefore, an engine which produces the same amount of pollution as a similar engine, but burns less fuel will have a higher emissions factor.

Figure 2-3 compares the current engine emissions with the NOx standards. Many of the older engines are approaching the limit, while most of the newer engines comply with ease. According to this standard, CFM56 engines are the cleanest, while the Rolls Royce RB211 engines are often borderline. As exhibited by Figure 2-3, no engines are shown to violate either of the standards. Compared with the noise standards, aircraft emission standards are not as stringent.

Figure 2-2

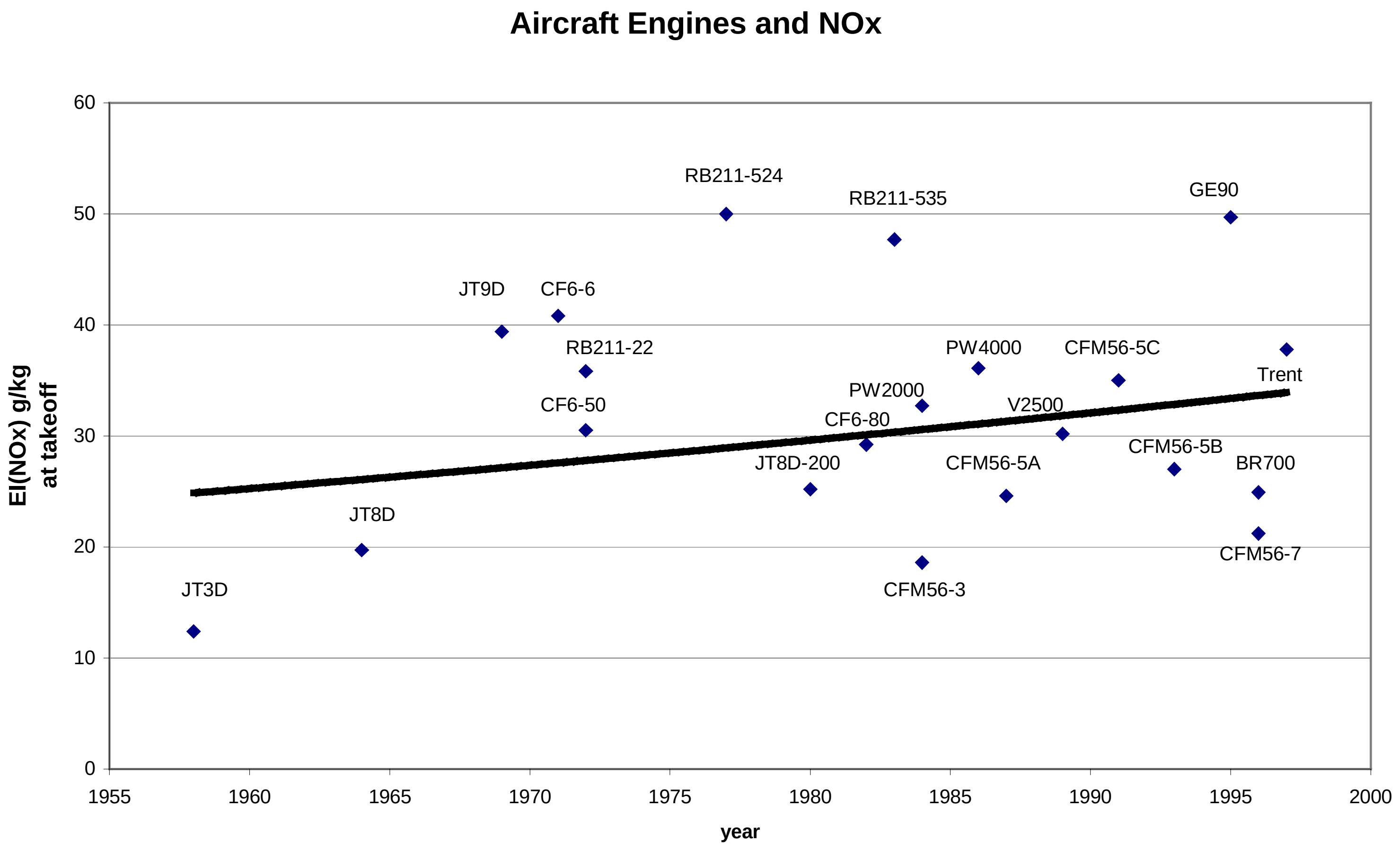
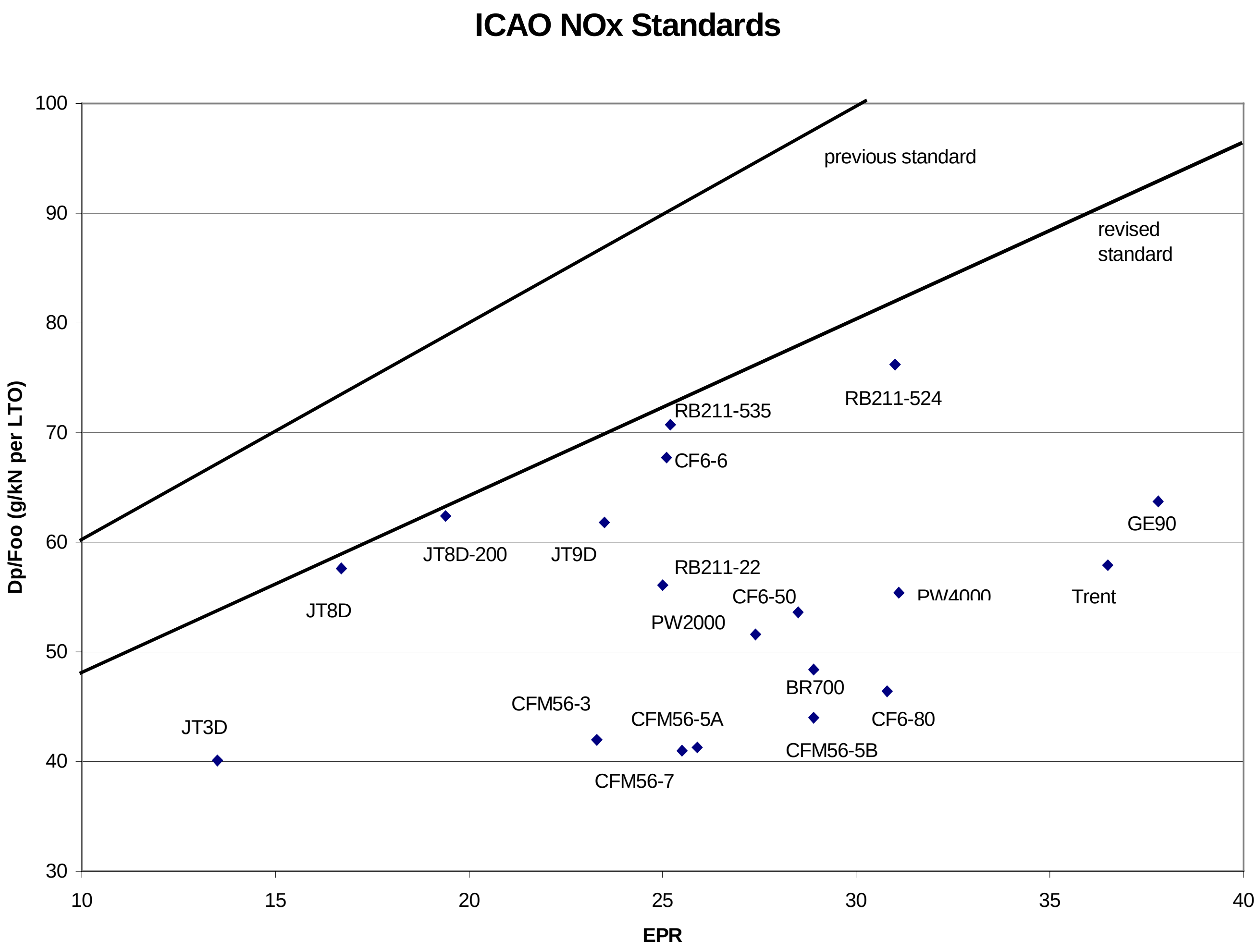

Aircraft Engines and NOx
EI(NOx) g/kg at takeoff
year
0
10
20
30
40
50
60
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
JT3D
JT8D
JT9D
CF6-6
RB211-22
CF6-50
RB211-524
RB211-535
JT8D-200
CF6-80
PW2000
CFM56-3
PW4000
CFM56-5A
V2500
CFM56-5C
CFM56-5B
GE90
BR700
CFM56-7
Trent

Figure 2-3


ICAO NOx Standards
previous standard
revised
standard
RB211-524
RB211-535
CF6-6
GE90
JT8D-200
JT9D
RB211-22
CF6-50
PW4000
Trent
JT8D
PW2000
BR700
CFM56-3
CFM56-5A
CF6-80
JT3D
CFM56-5B
CFM56-7
Dp/Foo (g/kN per LTO)
100
90
80
70
60
50
40
30
10
15
20
25
30
35
40
EPR

2.3 Conformity

The Clean Air Act requires the EPA to ensure that all federal actions conform to the appropriate state implementation plan. According to 40 CFR, Parts 6, 51, and 63, all new federal actions, programs, projects must not violate the National Ambient Air Quality Standards (NAAQS). The Federal agency responsible for the action must determine whether or not its actions conform with the applicable SIP. For airports, the FAA must ensure that airport expansion plans will not cause air quality conformity problems. If any conformity problems are shown initially in the environmental impact statement, the FAA must perform additional work and analysis to justify the project. Thus far, no airport expansion projects have been completely blocked because of air quality. However, conformity problems have occurred recently with projects at Seattle and St. Louis Airports.

2.4 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).

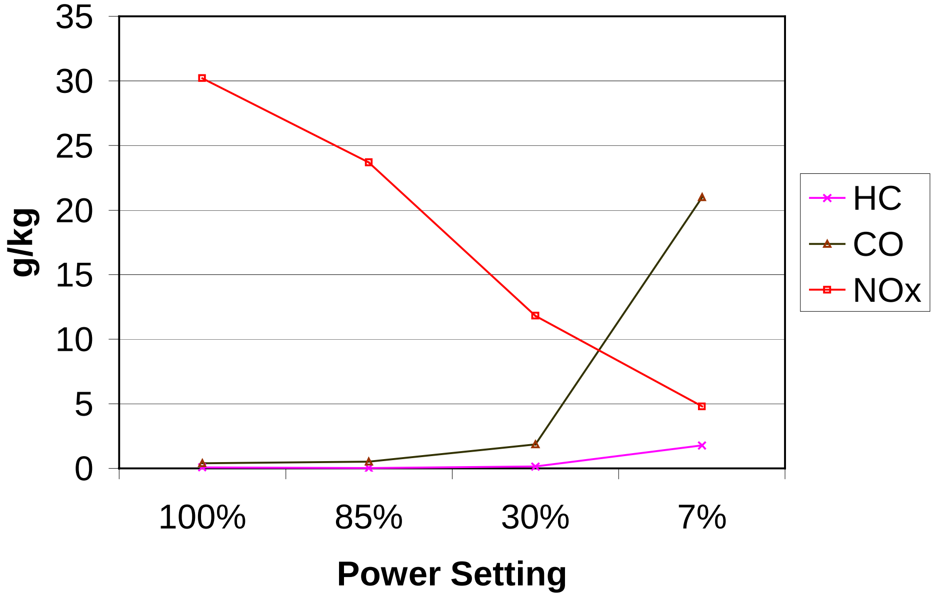
Engine emissions factors have the units of grams of pollutant per kilogram of fuel burned. To compute aircraft emissions, the emissions factor for each mode is multiplied by the amount of fuel burned and by the number of engines. Fuel consumed during each phase is computed by multiplying the fuel burn 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 2-4:

Table 2-4 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

Figure 2-4 shows the relationship between emissions factors for a Pratt and Whitney model 4158 aircraft engine. Hydrocarbons and carbon monoxide are products of incomplete combustion and vary inversely with power setting. NOx is a bi-product of combustion and is a function of temperature. Therefore, higher power settings produce larger amounts of NOx.

Figure 2-4 Emissions vs Thrust for PW 4158 engine



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.

2.5 Current Emissions Reduction Strategies

There are many proposed emissions reductions strategies for airports for both the landside and airside. Airside emissions reduction measures which are currently in-use include single-engine taxi, providing pre-conditioned air and 400 Hz electrical power for aircraft, using alternative fuel ground service equipment, and implementing emissions surcharges. Landside emissions reduction strategies primarily include reducing vehicle trips, reducing airport roadway congestion, and encouraging mass transit. Since approximately 20% of all air travelers at major airports rideshare (Higgins, 1994), reduction in vehicle trips will not be easily achieved. Most of the reduction in landside emissions will come from cleaner vehicles.

Increases in fuel efficiency of jet engines have resulted in increases of NOx. Although today’s engines produce significantly less unburned hydrocarbons and smoke, they produce 2-3 times the amount of NOx per kilogram of fuel burned than first generation jet engines. Increasing the thermodynamic efficiency of the engine is performed by increasing combustion temperatures. (Moxon, 2000). Although fuel efficiency offsets some of the NOx disbenefit, higher levels of overall NOx may be produced.

Currently, there are few emissions reduction measures in use for aircraft. The two most common strategies for aircraft are single-engine taxi and assessing emissions surcharges. Single-engine taxi primarily reduces VOCs and cannot be used on all types of aircraft. Emissions surcharges provide only marginal reductions in aircraft emissions and would face significant opposition from the airlines. Neither strategy would significantly reduce NOx emissions.

2.5.1 Single-Engine Taxi

For aircraft, the only emissions reduction strategy that is commonly practiced is single-engine taxi. It was originally performed by the airlines and military to save fuel during rising fuel costs. Since aircraft only need a minimal amount of power to taxi, single-engine taxi reduces emissions by avoiding unnecessary consumption of fuel. Although the remaining engine operates at a higher power setting, it operates more efficiently. Since aircraft engines produce large amounts of NOx at high power, and emit more unburned fuel at low power, single-engine taxi is projected to reduce VOCs and carbon monoxide. (Draper, Pernigotti, and Liang, 1997)

There are numerous advantages and disadvantages for single-engine taxi. While taxiing, engines are assumed to operate at idle or 7% power. At this power setting, carbon monoxide is the criteria pollutant most emitted. VOC emissions are also increased and NOx emissions are at their lowest. The majority of VOCs and carbon monoxide produced during the LTO cycle are emitted during the idle phase. Theoretically, for a two-engine aircraft, using single-engine taxi could reduce VOC and carbon monoxide emissions by 50%.

However, since the remaining engine must operate at a higher power-setting, single-engine taxi could slightly increase NOx. NOx emissions are proportional to power-setting, while carbon monoxide and hydrocarbon emissions are inversely related to power-setting. Additionally, all engines must run for two minutes prior to takeoff to achieve thermal stability, as well as two minutes after landing to cool down (Draper, Pernigotti, and Liang, 1997). This limits the duration of single-engine taxi. The number of engines that can be shut down depends on the location of the engines, aircraft weight, and aircraft size. For some aircraft, single-engine taxi is not feasible due to safety concerns. Directional control problems could occur because of the unbalanced thrust which results. Safety concerns include potential damage to ground equipment and personnel when the operating engine is accelerated to begin aircraft movement (EEA, 1995). Delta Airlines is recognized as a single-engine taxi "pioneer" (Pearl, 2000). Delta taxies on one engine whenever possible, even on three-engine aircraft such as the B727.

2.5.2 Aircraft Emissions Surcharges

Swiss airports are among the only airports in the world which levy fees based on aircraft air pollution. The airport authority believes that emissions fees provide airlines with an incentive to retire older, more polluting aircraft. Zurich Airport collects the emissions charges by adding them to the landing fees, which are assessed by weight. Depending on the amount of pollution generated, landing fees can be increased by up to 40%.

In Zurich (1997), Switzerland is attempting to reduce its air pollution emissions to 1960 levels, nationwide. Zurich Airport began charging based on emissions in 1991. Noise-related landing charges have been in use since 1980. Zurich converts the ICAO engine emissions factors into its own composite emissions factor by using Equation 2-6.

$$EEF = (NOx_{LTO} + VOC_{LTO}) / \text{max. thrust} \qquad (2\text{-}6)$$

The total NOx and VOC emissions per engine generated during takeoff are summed and the result is divided the engine's rated takeoff thrust. The result is used to classify aircraft. The aircraft classes and charges are shown in Table 3-4. Table 3-5 shows a sample list of aircraft, EEF, and Class.

Table 2-5 Aircraft Emissions Penalties at Zurich Airport

Emissions Class	EEF	Penalty added to landing fee
5	0 – 50	0%
4	50-60	5%
3	60-80	10%
2	80-100	20%
1	>100	40%

Table 2-6 Examples of Aircraft Emissions Classifications at Zurich

Class	Aircraft	Engine	EEF
5	A320	CFM56-5B4	44
	BAe 146-300	ALF 502R-5	44
	B737-400	CFM56-3-C1	49
4	B747-400	PW4056	51
	B757-200	PW2037	52
	A310-300	CF6-80C2	56
3	B747-200	JT9D-7R4G	61
	B727-200	JT8D-15	66
	MD-83	JT8D-217	73
2	BAC111-500	Spey MK12	88
	DC-10-30	CF6-50C2	95
1	B747-100	JT9D-7A	119
	B707-300	JT3D-3B	307

2.6 Dallas/Ft. Worth Metroplex – A Special Case

The Dallas/Ft. Worth Metropolitan Area was classified by the EPA as a moderate nonattainment area for ozone, as defined by the Clean Air Act Amendments of 1990. The region was required to demonstrate attainment of the 1-hour standard by November 1996, which did not occur. The DFW area was then reclassified by the EPA as serious non-attainment. The initial attainment deadline for "serious non-attainment" areas was November 1999. The region was unable to meet this deadline also. Since there is data which suggests that DFW is significantly impacted by ozone transport from the Houston-Galveston area and high background levels of ozone, the EPA has extended the attainment deadline to November 2007.

The Dallas/Ft. Worth Metropolitan area presents a special case in airport emissions. Dallas Love Field is a connecting hub for Southwest Airlines and DFW Airport functions as a connecting hub for both American and Delta Airlines. Fort Worth Meacham and Fort Worth Alliance Airports handle sizeable amounts of air cargo and charter traffic. As a result, the Dallas area boasts a tremendous amount of air travel activity for a region of its size. In 1999, DFW Airport was the third busiest in terms of aircraft operations and the fifth busiest airport in the world in terms of passengers handled (ACI, 2000). Therefore, the Dallas region has one of the highest amounts of airline activity per capita in the United States and aviation-related activities are responsible for a significant amount of ozone precursors in the Dallas area. Dallas, as with other sunbelt cities, is located in a VOC saturation region. This indicates that ozone formation is more sensitive to NOx emissions than VOC emissions and that the easiest way to reduce ozone concentrations is by reducing NOx. For the Dallas non-attainment region, a total of 581 tons of NOx per day from all sources were emitted in 1996 (TNRCC, 2000). DFW Airport was responsible for approximately 6% of this amount. Including emissions associated with Love Field, and Ft. Worth Meacham Airports, it is estimated that aviation-related activities are currently responsible for 8-9% of the total regional NOx.

Previously, only emissions reduction strategies which reduced VOCs for Dallas were addressed. Now, NOx reduction strategies are being focused on. In order to achieve attainment by 2007, the SIP modeling shows that a 45% reduction in total NOx emissions is necessary (TNRCC, 2000). Also included in the Dallas plan was a proposal to require gradual conversion to all-electric GSE by 2003. This proposal was approved by TNRCC and became law in April 2000. It proposes to reduce GSE emissions by 90% or 9.54 tons per day. Currently, this law is being challenged with a lawsuit filed by the Air Transport Association.

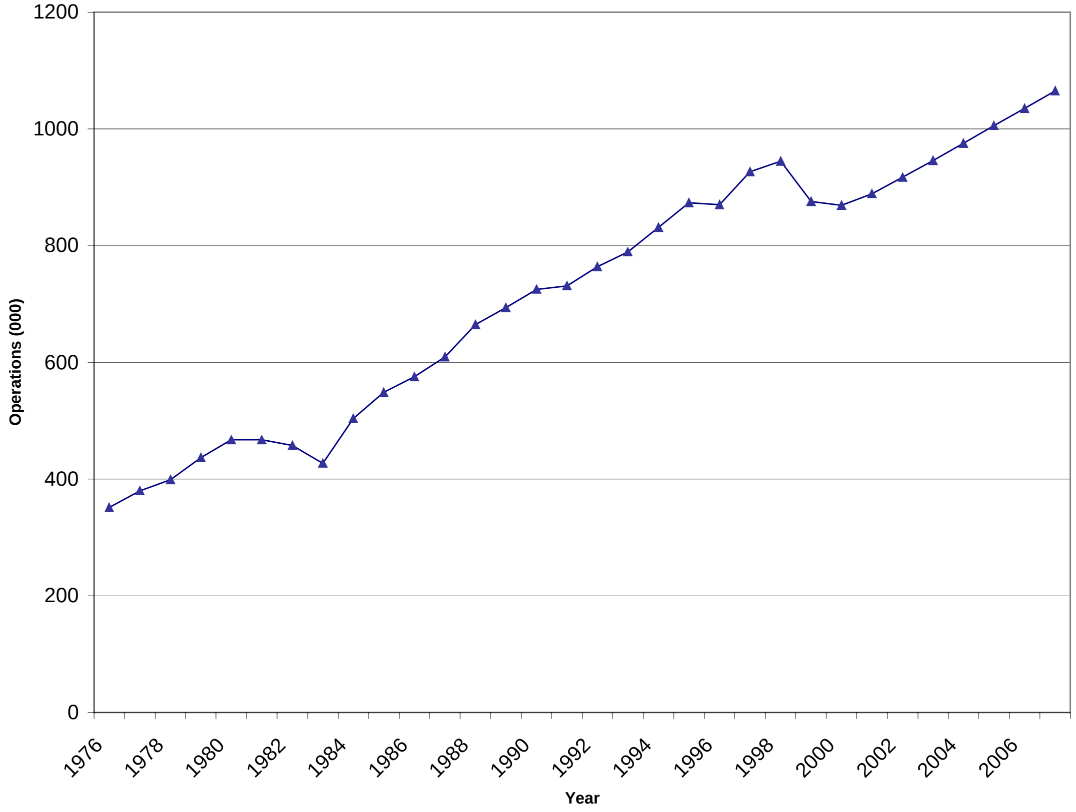
Roughly half of the VOCs at DFW Airport are produced by aircraft and the remaining are from GSE and automobiles. Nearly 95% of the aircraft VOCs are produced during taxiing. Single engine taxi is estimated to reduce VOCs at from aircraft by 25-35%, resulting in a net decrease for the airport of 15% (Rice and Walton, 2000). In Dallas, 2% of regional VOCs come from the airport, compared with 6% of the regional NOx. (TNRCC, 2000). Since there are no proposed VOC control strategies for the Dallas region, the relative contribution of the airport will probably stay the same in the future.

2.6.1 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. As discussed in the previous section, the relative contribution of NOx emissions from airports in some metropolitan areas 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 2-5 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 2-5 shows the airport emissions for 1996 and 2007.

Figure 2-5 Historical Operations Growth at DFW Airport



source: FAA, 2000

Table 2-7 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 2-6 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 2-8 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)

2.7 Restricting the Use of Reverse Thrust as an Emissions Reduction Strategy

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 NOx 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.

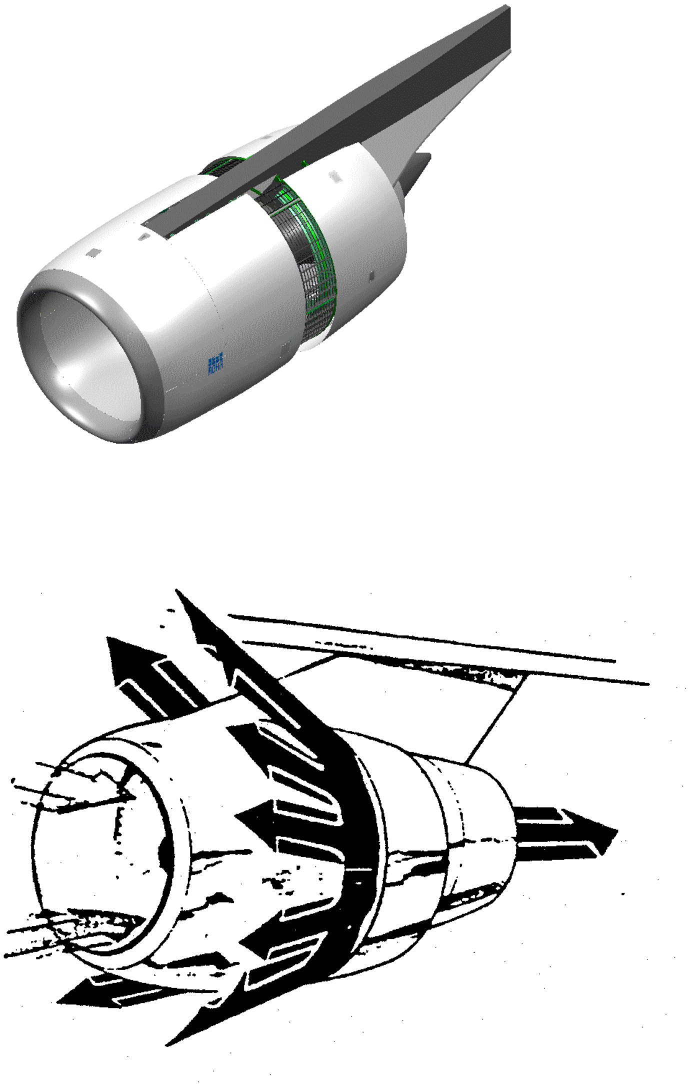
Thrust reversers are occasionally used to back aircraft away from boarding bridges. This is known as “power-backing”. There are a lot of characteristics which determine whether or not an aircraft will be power-backed. These include location and type of engines, layout of terminal area, ample room, proximity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

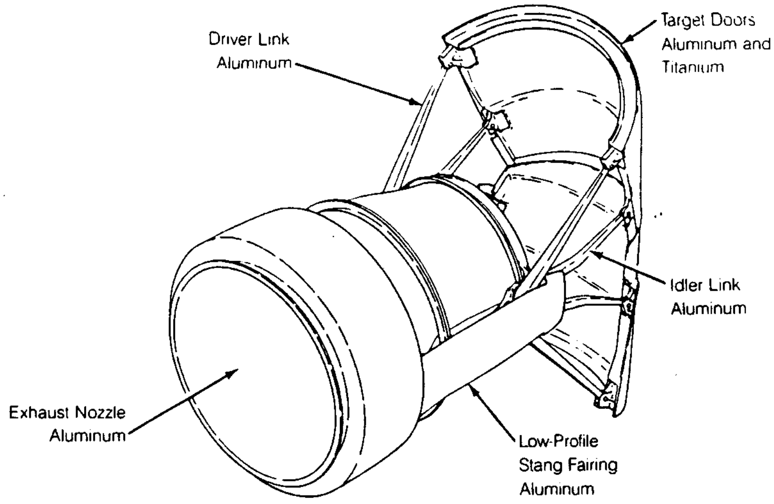
American Airlines is currently the only carrier which practices widescale power-backing. American prefers to power-back whenever possible and does so unless safety is compromised (Hotard, 2000). In the past, Continental has power-backed aircraft. A few years ago, the airline decided that power-backing was “too noisy” and “unprofessional” and ceased the practice (Moody, 2000). TWA, Northwest, and USAirways also reported occasional power-backs, only when an aircraft tug has broken down (TWA, 2000; Berg, 2000; USAirways, 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 2-6 and 2-7 show the two different types of thrust reversers.

Figure 2-6 Examples of Cascade Thrust Reversers



source: BF Goodrich Aerospace

Figure 2-7 Example of Clamshell Thrust Reverser



source: BF Goodrich Aerospace

2.8 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 2-8 through 2-11, 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 2-12 and 2-13 show probability density functions of

Figures 2-8 and 2-9. 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.

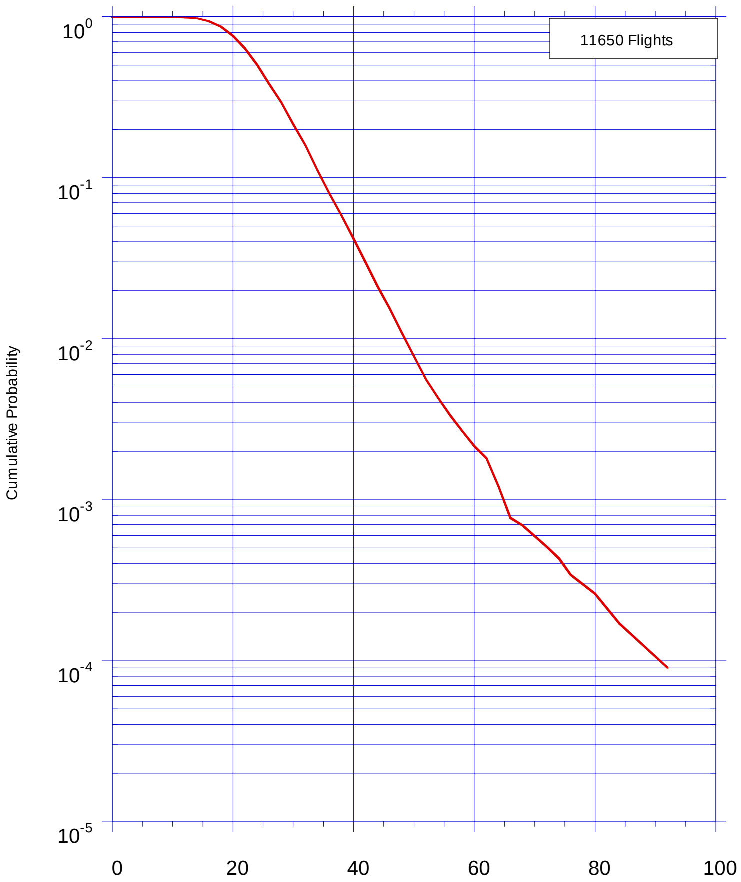


Figure 2-8 Cumulative Probability of Time With Thrust Reversers Deployed for B737-400

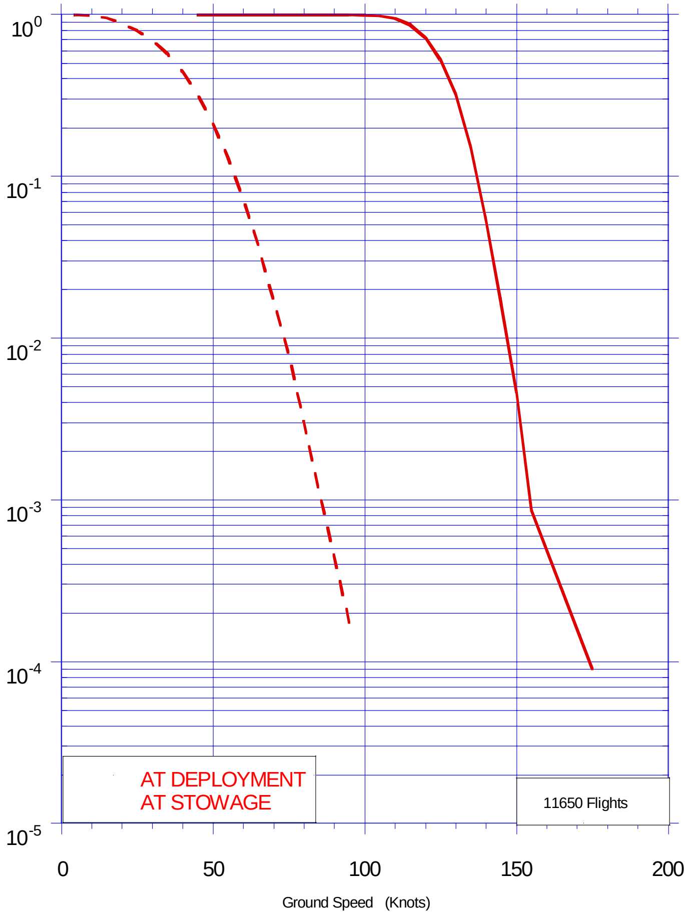


Figure 2-9 Cumulative Probability of Speed at Thrust Reverser Deployment and Stowage for B737-400

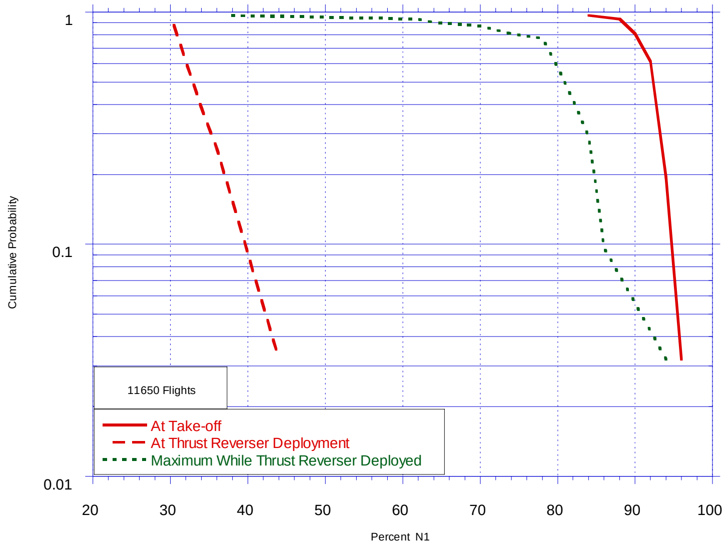


Figure 2-10 Cumulative Probability of Percent of N_1 For B737-400

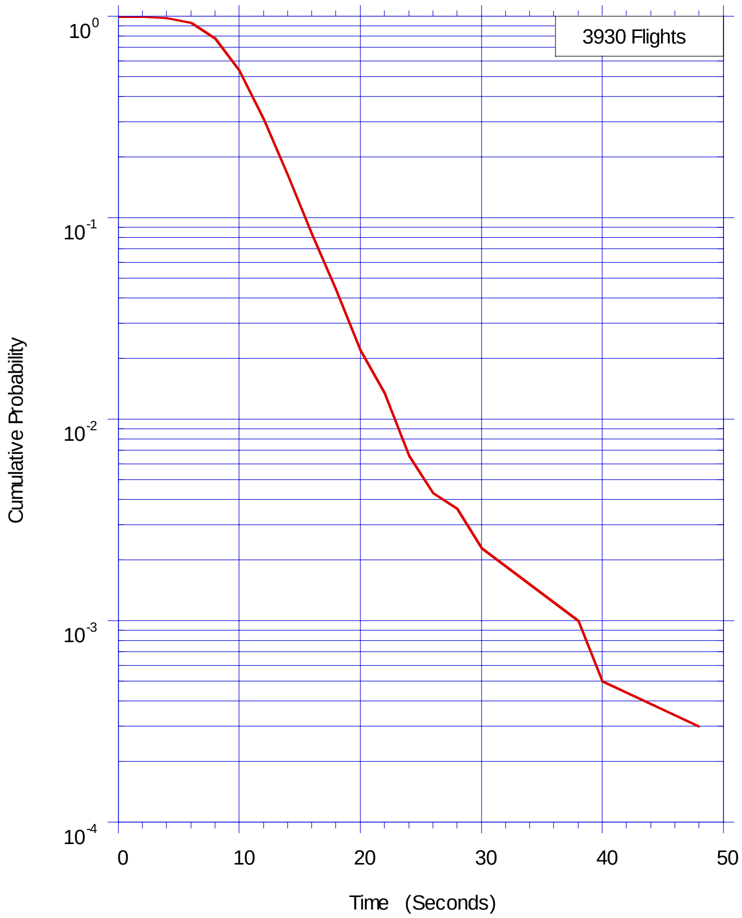


Figure 2-11 Cumulative Probability of Time With Thrust Reversers Deployed for MD-80

Figure 2-12

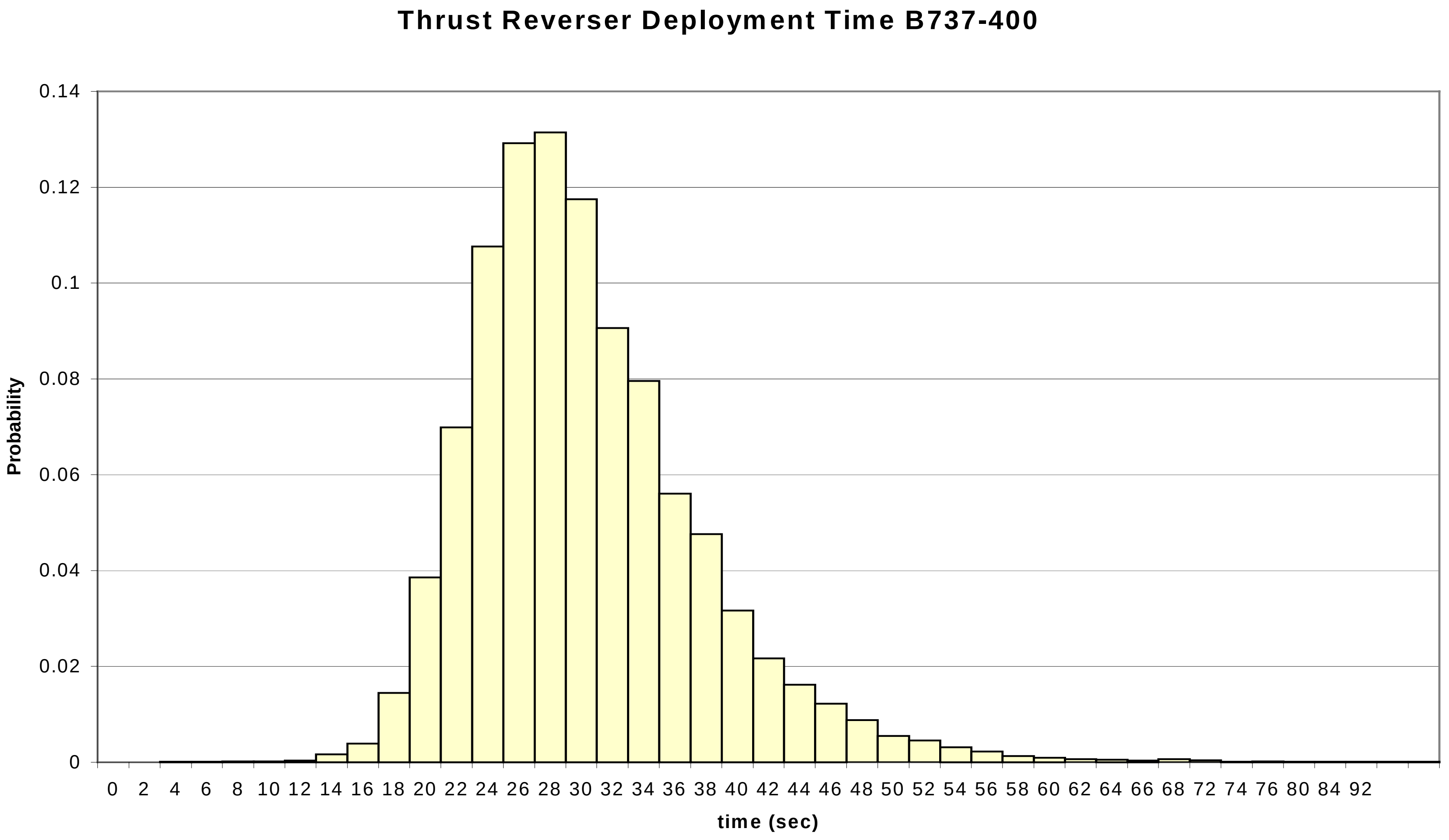
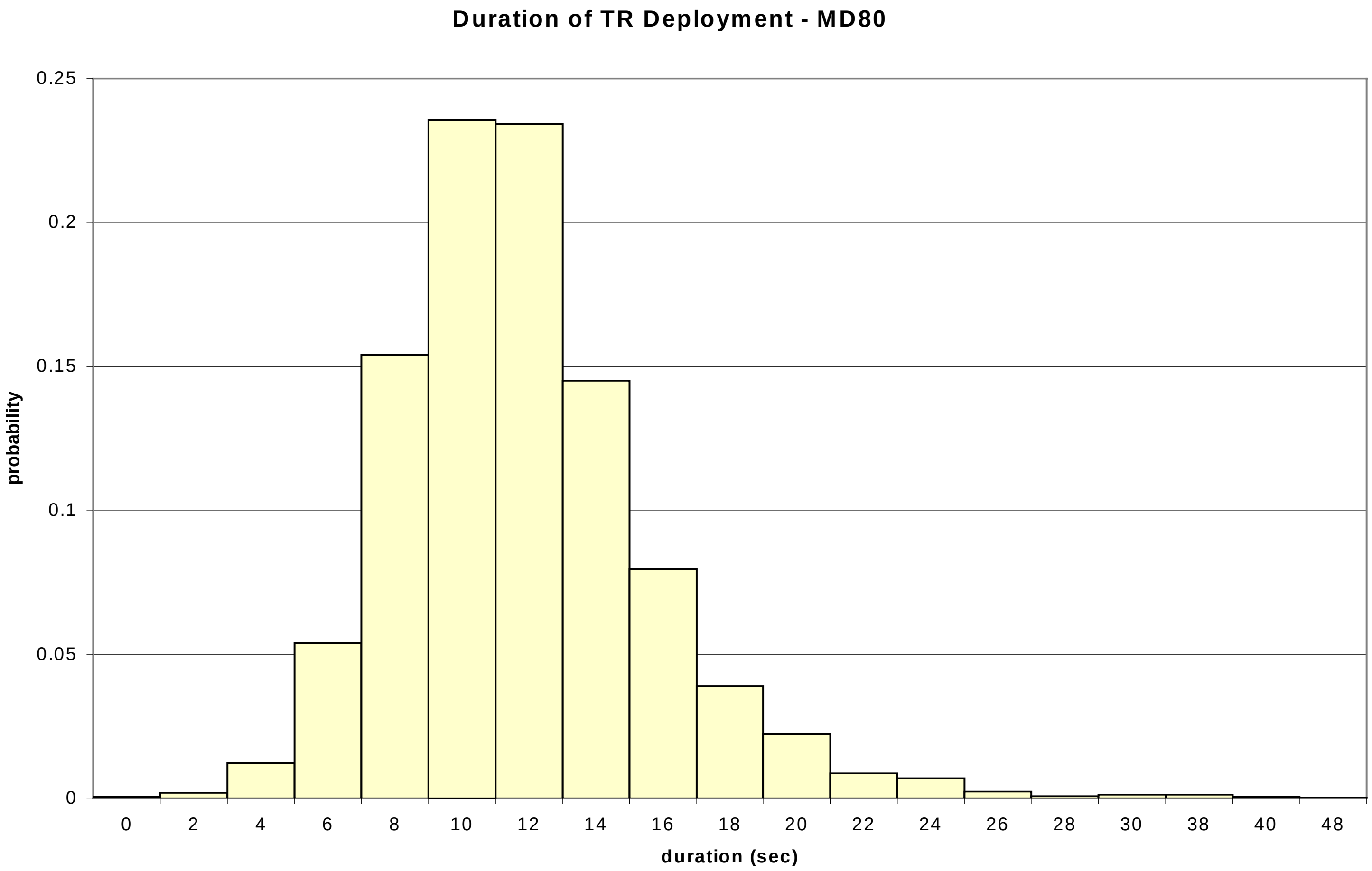

Thrust Reverser Deployment Time B737-400
Probability
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
time (sec)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 72 74 76 80 84 92

Figure 2-13


Duration of TR Deployment - MD80
probability
0.25
0.2
0.15
0.1
0.05
0
duration (sec)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
38
40
48

2.9 Modification of Emissions Factors

In Baughcum, Tritz, et al (1996), the development of a database for worldwide emissions estimates and fuel consumption for aircraft is discussed. The emissions inventories were developed under the NASA High Speed Research Systems Studies, Task Assignment 53. A detailed database of fuel burned, NOx, VOC, and CO emissions for scheduled air traffic was developed for each month in the year 1992. Computed emissions are for all phases of flight, including cruise. In 1992, global fuel use by aircraft was estimated to be 9.5×10^{10} kilograms and 1.2×10^{9} kilograms of NO_2 were emitted.

Recently, airlines have become interested in computing emissions during entire flights. However, aircraft engine manufacturers are required to publish emissions factors or indices for only 4 modes: idle, approach, takeoff, and climbout. Calculations with these factors only represent an approximation of emissions in the vicinity of an airport. During other phases of flight, different power settings are used. Aircraft engine emissions vary with power setting. In order to compute emissions at other power settings, new emissions factors are needed.

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.*

$$W_{ff} = \frac{W_f}{\theta_{amb}^{1.5}} \tag{2-7}$$

$$\text{EI(HC,CO)} = \mathit{REI(HC,CO)} / \delta^4_{amb} \tag{2-8}$$

$$\text{EI(NOx)} = \mathit{REI(NOx)} * \theta_{amb} * e^H \tag{2-9}$$

where:

W_f = fuel flow
W_{ff} = fuel flow factor
δ, θ = temperature and pressure ratios
e^H = humidity correction factor

$$\theta_{amb} = \frac{T_{amb}}{288.16} \tag{2-10}$$

$$\delta_{amb} = \frac{P_{amb}}{101.32} \tag{2-11}$$

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.

2.10 Industry Perspectives

Sacramento International Airport prohibited power-backing to specifically reduce aircraft emissions (Humphries, 2000). Emissions savings were computed by eliminating one minute of high thrust operation from the landing/takeoff cycle. This amounted in a reduction in NOx of 3.8% for aircraft (Humphries, 2000). This method of calculation is not thought to be accurate, as not all airlines practice power-backing and the average reverse thrust use during power-backing is less than one minute. Other California airports which do not allow power-backing include Ontario and LAX.

At Munich International Airport, reverse thrust at greater than idle power is prohibited. (Boeing, 2000). Munich considers idle power is considered to be a power setting of less than 30% (Kanzler, 2000). Munich was specifically designed with longer runways (4000 meters) to enable aircraft to land without using reverse thrust.. Even with the extra distance added, landing rolls do not appear to be longer, even on icy or wet runways. (Kanzler, 2000). At Munich, reverse thrust is prohibited primarily for noise reasons. The present airport opened in 1992 and reverse thrust usage was restricted to minimize complaints from the surrounding community. Zurich Airport also restricts reverse thrust usage to emergencies only. It also reports that landing rolls are not significantly longer during wet or icy conditions (Fleuti, 2000).

American prefers to power back its planes away from boarding gates whenever possible (Vance, 2000). In Austin, American power-backs at only 3 of its 5 gates, because of concerns by the adjacent airlines (Vance, 2000). American prefers power-backing because it is easier and faster than using an aircraft tow (Vance, 2000). Power-backing minimizes GSE usage and doesn’t require connecting and disconnecting a. towbar. Typically, only rear-engined aircraft are power-backed to avoid debris ingestion. Rear-engined aircraft operated by American aircraft include MD-80, B727, F100.

3.0 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 NOx 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).

In Woodmansey and Patterson (1994), a methodology for predicting aircraft emissions by aircraft weight is presented. This method is useful when the specific aircraft engine type is unknown or when emissions factors are not available. A regression analysis is performed using values of aircraft weight and emissions per LTO for each pollutant. Emissions estimates are also developed for CO_2 and N_2O, important greenhouse gases which are not normally quantified when developing airport emissions inventories.

Popp, Bishop, and Stedman (1999) sampled nitric oxide emissions from aircraft at London Heathrow by optical remote sensing. Equipment typically used to measure automobile exhaust emissions was used for aircraft exhaust emissions. Using a UV spectrometer, CO_2 concentrations were measured, which were converted to NO concentrations by using the NO/CO_2 ratio and the carbon/hydrogen ratio of the fuel being burned.

URS Greiner (1998) developed an emissions inventory for DFW Airport. Emissions estimates of CO, NOx, 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.

In Borowiec, Qu, and Bell (2000), emissions inventories are developed for the 27 commercial service airports and 233 general aviation (GA) airports in Texas for the years 1996, 1999, and 2007. EDMS was used to compute the aircraft and GSE emissions at the commercial service airports only. The EPA's AP-42 software program was used to compute aircraft emissions for the GA airports. Air traffic data and forecasts were obtained from the FAA Terminal Area Forecast. Fleet mix information for the commercial service airports in 1996 was obtained from the

Bureau of Transportation Statistics (BTS) database. Each airport's 1996 fleet mix was used in developing the 1999 and 2007 forecasts.

In computing the aircraft emissions, the mean morning mixing height values were used for each airport. In EDMS, TIMs for approach and climbout are determined by the mixing height. The mixing height typically increases during the day, reaching a maximum during the afternoon (Wark, Warner, and Davis, 1998). As a result, Borowiec, Qu, and Bell (2000) may have underestimated the aircraft emissions for many Texas airports.

In Boyle (1996), the absence of particulate emissions factors for jet aircraft engines was focused on. It was noted that "previous studies of air pollutants have found that particulates derived from mobile sources have more serious adverse impacts than other anthropogenic emissions." Boyle (1996) proposed that particulates from jet aircraft were highest during takeoff and climbout and evidence of this was found near Los Angeles International Airport (LAX). Soil samples were collected near LAX and analyzed for heavy metals and hydrocarbons. Levels of zinc, copper, and beryllium were found to be twice as high as the control, lead was 50% higher, while cobalt and vanadium were nearly 30% above the control. Particulates from aircraft exhaust emissions were all below 1.5 µm, which are able to penetrate deep into human lungs. Boyle (1996) also notes that particulate emissions differ by aircraft engine type and that vanadium can be used as a tracer species for aircraft exhaust.

3.2 Air Quality Regulation and Policy

Hawthorn (1991) summarized the transportation-related provisions of the 1990 Clean Air Act Amendments (CAAA). State implementation plans for metropolitan areas were developed for areas which are deemed to be in violation of the NAAQS. The emissions reduction measures to be implemented depend on the severity of the violation. Hawthorn (1991) provided a good discussion of the terms and regulatory context associated with conformity assessments for transportation. No project may cause or contribute to new violations of any NAAQS, increase the frequency or severity of NAAQS violations, or delay the attainment of any NAAQS or emissions reductions. For airports, the FAA is required to prepare an EIS for any action which may adversely effect the environment. The process for assessing the air quality impacts involves the following steps (Draper, Pernigotti, and Liang, 1997):

1) project definition – scope and all project options, build/no-build
2) inventory of emissions – potential environmental impact
3) indirect source review – additional travel demand generated by new facility
4) conformity determination
5) assessment of NAAQS

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. The area was classified as a moderate nonattainment area for ozone by the Clean Air Act Amendments of 1990.

The region was required to demonstrate attainment of the 1-hour standard by November 1996, which did not occur (TNRCC, 2000). The DFW area was reclassified by the EPA as serious non-attainment. The initial attainment deadline for "serious non-attainment" areas was November 1999 (TNRCC, 2000). The region was unable to meet that deadline also. Since there is data which suggests that DFW is significantly impacted by ozone transport from the Houston-Galveston area and high background levels of ozone, the EPA has extended the attainment deadline to November 2007 (TNRCC, 2000).

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

Category/Measure	Estimated NOx reduction in 2007 (tpd)
Federal on-road measures • Phase II reformulated gasoline • Tier II vehicle emissions standards • Low-emitting vehicle program	93
Federal off-road measures • Lawn and garden equipment • Locomotives • Spark ignition standards for vehicles and equipment	48
TNRCC issued rules	
• Major point source NOx reduction in 4 counties	129
• Airport GSE electrification	9.54
• Delayed operation of construction equipment	2.5
DFW Local Initiatives	
• Speed limit reduction in 9 counties	5.42
• Transportation control measures in 4 counties	4.73

Jamieson (1990) discussed the technological improvements achieved in reducing aircraft engine emissions and the development of ICAO and EPA aircraft emissions standards. Although international standards have been developed for aircraft emissions, it us up to individual countries to enforce them and only a few have formally done so. Jamieson (1990) also compared the ICAO standards with engine emissions, by plotting D_p/F_{oo} and engine pressure ratio. It was concluded that further reduction in NOx from aircraft engines “without resort to drastic approaches is extremely limited” and a constant NOx emissions standard for aircraft with no adjustment for pressure ratio is suggested.

Perl, Patterson, and Perez (1997) discuss a strategy for pricing aircraft emissions at Lyon-Satolas Airport in France. Costs are developed using an aircraft emissions inventory and monetary evaluation techniques used to estimate air pollution costs from surface transportation. Four methods of price estimation are presented. In Scenario A, a "rural/minimal" estimate developed, which hypothesizes that aircraft emissions have little effect on the metropolitan environment. In Scenario B, an "urban/minimal" estimate is developed, which assumes that airport pollution does not become part of the region's airshed. In Scenario C, a "rural/potential" estimate is developed, which seeks to preserve rural natural resources, such as forestry and agriculture. In Scenario D, an "urban/potential" estimate is developed, which would be analogous to an city-center airport, where damage to public health and the infrastructure would be high. It is concluded that pollution costs ranged from $3.6 million to $6.6 million in 1984 and projected to increase from $9.5 million to $17.4 million by 2015.

Morrell and Lu (2000) attempt to quantify the societal costs of aircraft noise and air pollution for Amsterdam's Schiphol Airport. Comparisons are made with current environmental pricing strategies in use. For aircraft noise, a hedonic price method, which takes into account property values near the airport, is incorporated. For air pollution, a direct valuation method is used. Four previous studies which reference monetary impacts of air pollution are referenced, and an average value from those studies is used. The total social cost of aircraft noise in Amsterdam is estimated to be $143 million annually, or $361 per flight. For aircraft emissions, the average social cost is $56 million annually or $403 per flight.

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 NOx 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 NOx 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 NOx by 75-80%. Electric GSE were found to reduce both hydrocarbon and NOx 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 coffecients 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 NOx Emissions

Few studies were found which focused specifically on airports' impact on urban air quality and the contribution of airports to regional NOx emissions. No studies were found where a photochemical grid model was used to model the effect of the airport. Moussiopoulos et al (1997) used a dispersion model to show the impact of the new Athens airport on air quality. Dispersion of VOCs, carbon monoxide and NOx away from the airport are modeled using the European Zooming Model, but the photochemical reactions are not modeled.

Because of the significant concentration of NOx 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 NOx 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 NOx 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.

4.0 EXPERIMENTAL DESIGN and DATA COLLECTION

This chapter discusses the experimental design used to measure thrust reverse usage and the method of data collection which was devised. Experiments were designed for both landing aircraft and powerbacks, using the results of the preliminary analysis. Selection of the sampling location and the special design of the data collection stations themselves are discussed. Photos of the data collection station are shown and the data reduction process is presented.

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.

Temperature affects aircraft performance during both takeoff and landing. Higher temperatures result in lower air density, which results in a lower output of engine thrust. Therefore, thrust reversers are slightly less effective at higher temperatures. Additionally, higher airport elevations also result in lower air density, which also reduce engine thrust output.

An aircraft’s airspeed is computed by adding the headwind to the ground speed. A tailwind is considered to be a negative headwind. When flying into a headwind, an aircraft’s airspeed is increased by the amount of the headwind. Therefore, less ground speed is necessary for the wings to maintain an equal amount of lift. When landing into a headwind, an aircraft’s touchdown speed may be slightly less, resulting in a reduction in the amount of thrust reverse needed. When the runway has a slope, gravity may increase or decrease the length of the landing roll. When landing on an uphill gradient, less work is required to slow the airplane, resulting in less thrust reverse usage. The opposite applies when landing on a downhill gradient.

The commercial aircraft industry is dominated by two manufacturers: Boeing and Airbus. McDonnell Douglas merged with Boeing in 1996 and McDonnell Aircraft and Douglas Aircraft merged in the 1980s. Prior to its merger with McDonnell, Douglas Aircraft Company produced the DC-8, DC-9, and DC-10 aircraft. The DC-9 Super 80 entered service in 1980 and was renamed MD-80 after Douglas merged with McDonnell. McDonnell Douglas also developed the MD-11 and MD-90. Over the years, Boeing has produced the B707, B727, B737, B747, B757, B767, and B777 aircraft. The B707 and B727 are no longer in production. The only B737 versions in production are the B737-600, B737-700, B737-800, and B737-900. The new B717 was inherited through Boeing’s merger with McDonnell Douglas, where it was previously known as the MD-95.

Airbus entered the commercial aircraft business in the early 1970s. It is a consortium of European aircraft manufacturers based in Toulouse, France. Airbus has produced the A300, A310, A320, A330, and A340 aircraft. The A380 New Large Aircraft is currently being developed and may be operational by 2007. Table 4-1 shows commercial aircraft in service at Austin/Bergstrom International Airport (ABIA) during November 2000.

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

Aircraft manufacturers typically produce several versions of an aircraft type. For example, for there are 9 versions of the Boeing B737 in operation today: B737-100, B737-200, B737-300, B737-400, B737-500, B737-600, B737-700, B737-800, and B737-900. The 100 and 200 are the oldest versions and have slender, cigar-shaped, noisy engines. The design was drastically changed in 1984, when the B737-300 entered service. The fuselage was lengthened and the aircraft was re-engined.

Since 1984, several more B737 versions have been developed, featuring various modifications. The B737-600, B737-700, B737-800, and B737-900 are the most current versions and are commonly known as B737-NG for “next-generation”. For this experiment, B737-300 and later aircraft were grouped into one category, as drastic design changes were implemented after the 200 series model.

Examples of airlines and aircraft in service at ABIA are shown in Figures 4-1 through 4-6. These photos were obtained from the author’s personal airplane collection and photographed by the author.

Figure 4-1 American Airlines MD-80

Figure 4-2 Southwest B737-200

Figure 4-3 TWA DC-9

Figure 4-4 Southwest Airlines B737-300

Figure 4-5 Delta Airlines B727

Figure 4-6 American Airlines B757

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_0 *: 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 β 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 ϕ, which is computed using a trial number of replications *n* and the sample variance, the number of replications needed to achieve an acceptable β can be iteratively determined.

The parameter ϕ is defined in equation 4-1:

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

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
σ = 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:

$$\phi^2 = 0.196n \qquad (4\text{-}2)$$

Next, we find the number of replications needed to achieve an acceptable level of β.

Table 4-6 Iterations to Achieve an Acceptable β

n	ϕ^2	ϕ	ν_1 numerator df	ν_2 error df	β
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 β=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 de determined. A common value for *e* is ±3%, which translates into a range of ±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).

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

Solving for n, we get

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

where $$n_0 = \frac{z_{\alpha/2}^2 S^2}{e^2} \tag{4-5}$$

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 4-8, 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 4-9 and 4-10.

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 and a histogram is shown in Figure 4-11. 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.

Figure 4-7 Airport Layout Plan

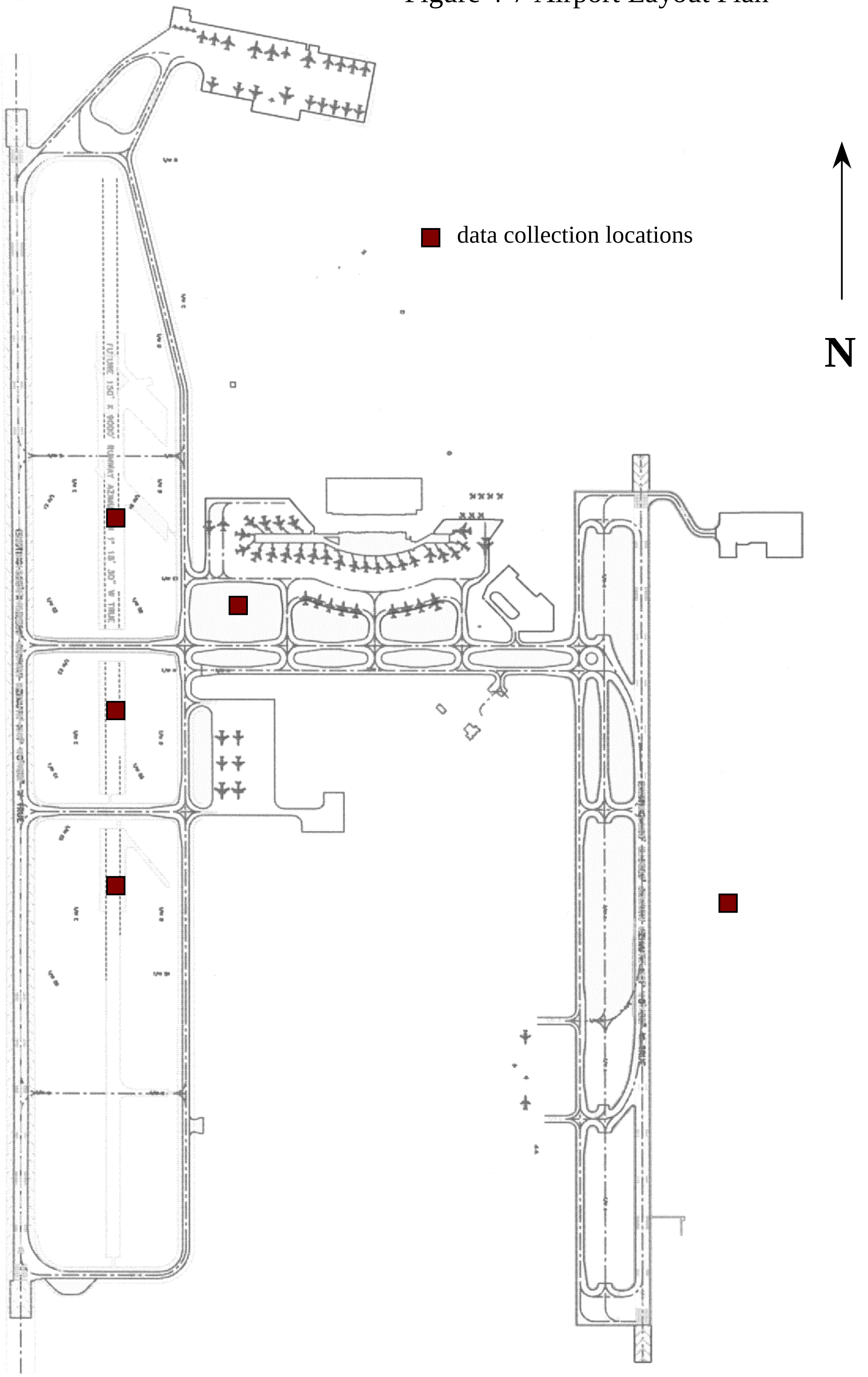


Figure 4-8 East Runway Data Collection Station

Figure 4-9 West Runway Data Collection Station

Table 4-7 ABIA Hourly Arrivals

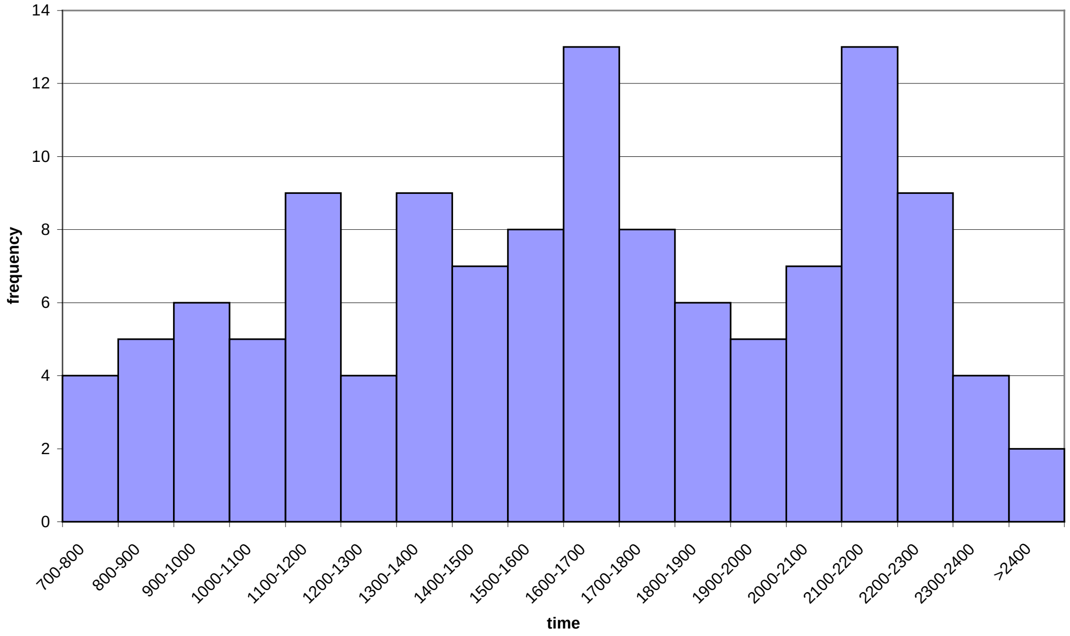
time	arrivals
700-800	4
800-900	5
900-1000	6
1000-1100	5
1100-1200	9
1200-1300	4
1300-1400	9
1400-1500	7
1500-1600	8
1600-1700	13
1700-1800	8
1800-1900	6
1900-2000	5
2000-2100	7
2100-2200	13
2200-2300	9
2300-2400	4
>2400	2

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

Figure 4-10 Distribution of Arriving Aircraft Times at ABIA



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 4-8.

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.

4.10 Summary

This chapter presents the methods of experimental design used to sample thrust reverse usage at Austin/Bergstrom International Airport. The factors thought to influence thrust reverse usage are presented and characteristics of the aircraft types which service the airport are discussed. The experimental 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. A sample size of 624 was needed to obtain the desired level of precision. For power-backs, a simple random sample was selected for the experimental design. A sample size of 74 was needed to achieve an acceptable margin of error.

Data collection stations were setup along both runways and behind American Airlines' gates 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. The videotapes were analyzed and the observations were transferred to a computer spreadsheet.

5.0 DATA ANALYSIS

This chapter analyzes the thrust reverse data which was collected and summarizes the results. Histograms are presented to show the distribution of thrust reverse usage among each aircraft type and airline. Analysis of variance is performed to isolate the factors influencing thrust reverse usage during landing and the interaction between certain factors is also explored. A relationship among headwind during landing is also examined, differences between cascade and clamshell reversers are compared, and a confidence interval is developed for the power-backing data.

5.1 Reverse Thrust Usage During Landing

5.1.1 Summary of Results

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.

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

Secondly, to maximize operational efficiency and profitability, airlines choose to operate certain aircraft on certain routes. For example, large, widebody aircraft are typically operated on long-haul flights or where there is sufficient demand. For this reason, the largest aircraft operated by a passenger airline into ABIA is the Boeing B757, by American. Although American operates widebody aircraft, such as the B767, B777, and DC-10, it typically uses these aircraft on longer flights.

The thrust reverser usage results obtained from this experiment were found to be slightly lower than results obtained from other studies. Only three other sources were found which contained data on thrust reverser usage: Statistical Loads Data for Boeing 737-400, Statistical Loads Data for Boeing MD-80, and Statistical Loads Data for Boeing 767, published by the University of Dayton Research Institute for the Federal Aviation Administration. In these reports, many parameters of aircraft operation were computer-recorded, in addition to thrust reverser usage. The data is presented only graphically, in the form of cumulative probability distribution plots, with a log-linear scale. When the report authors were contacted, the data used to plot the cdfs were obtained. Using this data, probability density functions were developed and the mean thrust reverser deployment times could then be approximated.

For the B737-400, the mean thrust reverser deployment time from the UDRI study was approximately 26 seconds. For the MD-80, mean deployment time was approximately 12 seconds. In this experiment, the usage for the newer B737s was 17.1 seconds and 14.4 for the MD-80. The difference in times can be explained by the way in which the data was collected. The B737-400 has CFM-56 high bypass turbofan engines, with cascade thrust reversers. When a cascade reverser is deployed on this engine, the engine nacelle gently slides backwards and the engine itself must “spool-up” to the reverse thrust power setting. When the reverser is stowed, the pilot must idle the engine first, before closing the nacelle. These procedures can easily add several seconds from the time at which the reverser is initially deployed, until it is completely stowed. For the MD-80, this process is much faster, due to the clamshell design.

For this experiment, thrust reverser 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.

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

Figure 5-1 shows the distribution of reverse thrust usage for all observations during landing and breaks the observations down by aircraft type. The differences in sample size and usage among each aircraft type can easily be discerned. After summing all aircraft types, the grouped distribution closely resembles a normal distribution, as expected, shown by Figure 5-2. Figures 5-3 and 5-4 show the usage by B737 aircraft. Newer B737s are operated by a total of 6 airlines at ABIA, dominated by Southwest. Older B737s are operated only by United and Delta. The difference in reverse thrust usage is very noticeable for the older B737s. On average, Delta uses reverse thrust for 3 seconds less than Southwest.

Boeing 727s, first produced in 1963, are among the oldest jet aircraft still being operated by passenger airlines. The more common, stretched B727-200 was first produced in 1968. Boeing ceased production of the B727 in 1984. United and Delta are the only airlines which operate B727s at ABIA. United and Delta operate B727s very differently during landing. The difference in reverse thrust usage between the two approached 5 seconds, the largest difference between any airline-same aircraft combination.

Figures 5-7 and 5-8 show usage by the DC-9 and MD-80. Both aircraft have similar averages, reflecting similarities in the design. DC-9s are operated by Northwest and TWA, while the MD-80s are operated by American, Continental, Delta, and TWA. The DC-9 is the aircraft least flown into ABIA, while the MD-80 is the second most popular, dominated by American Airlines.

The differences in thrust reverser usage by airline for the same aircraft type are thought to be the result of pilot training and airline policy. Figures 5-9 and 5-10 show examples of the aircraft-airline interaction that is present in the results. When interaction is present, the difference in response between the levels of one factor is not the same at all levels of the other factors. It is assumed that airlines may operate different aircraft types differently. In order to evaluate interaction, comparisons must be made between two or more airlines operating the same aircraft types. With this experiment, only three comparisons could be made for aircraft-airline interaction.

Continental and Delta are the only airlines which operate both the B737-300s and the MD-80 at ABIA. Delta and United are the only carriers which both fly the B737-300 and B727 at ABIA. Delta and Southwest are the only airlines which operate the older and newer B737s.

In Figure 5-9, when comparing B737-300s and B727s operated by United and Delta, the difference in reverse thrust usage between United's aircraft (4.5 seconds) is much greater than the difference between Delta's aircraft (0.5 seconds). This difference indicates the presence of interaction. Delta and United operate their B737s and B727s differently. If there were no interaction between the airlines, the difference between the two aircraft types for both airlines would be the same and the lines in Figure 5-9 would be parallel. In Figure 5- 10, interaction is noticed between B737s and MD-80s operated by Continental and Delta.

Figure 5-1

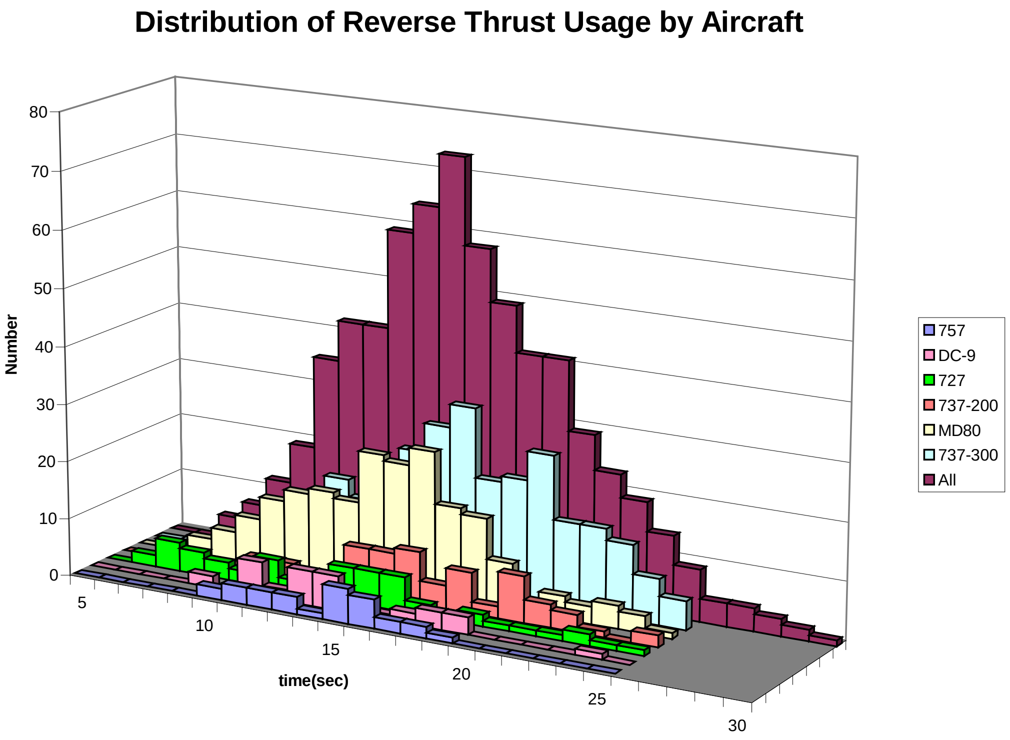


Figure 5-2

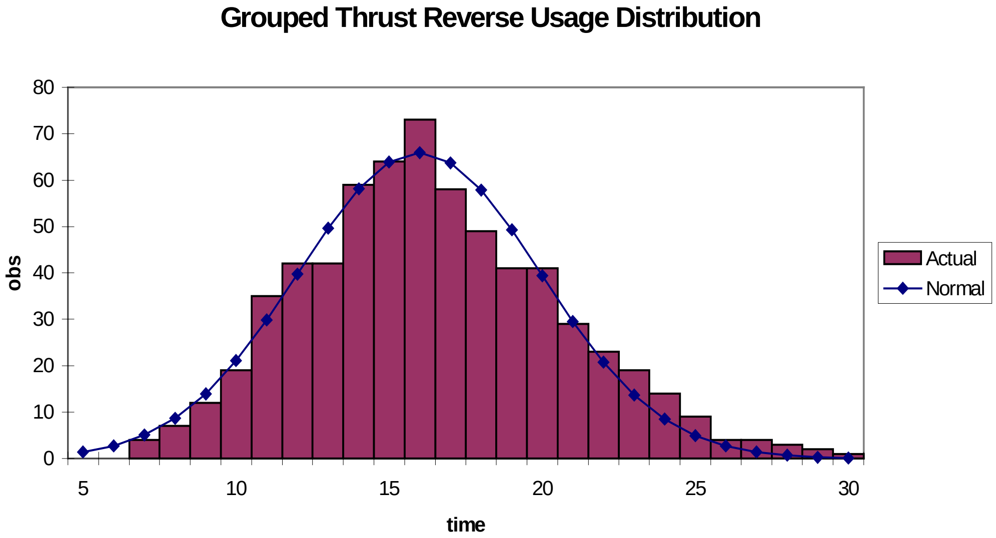


Figure 5-3

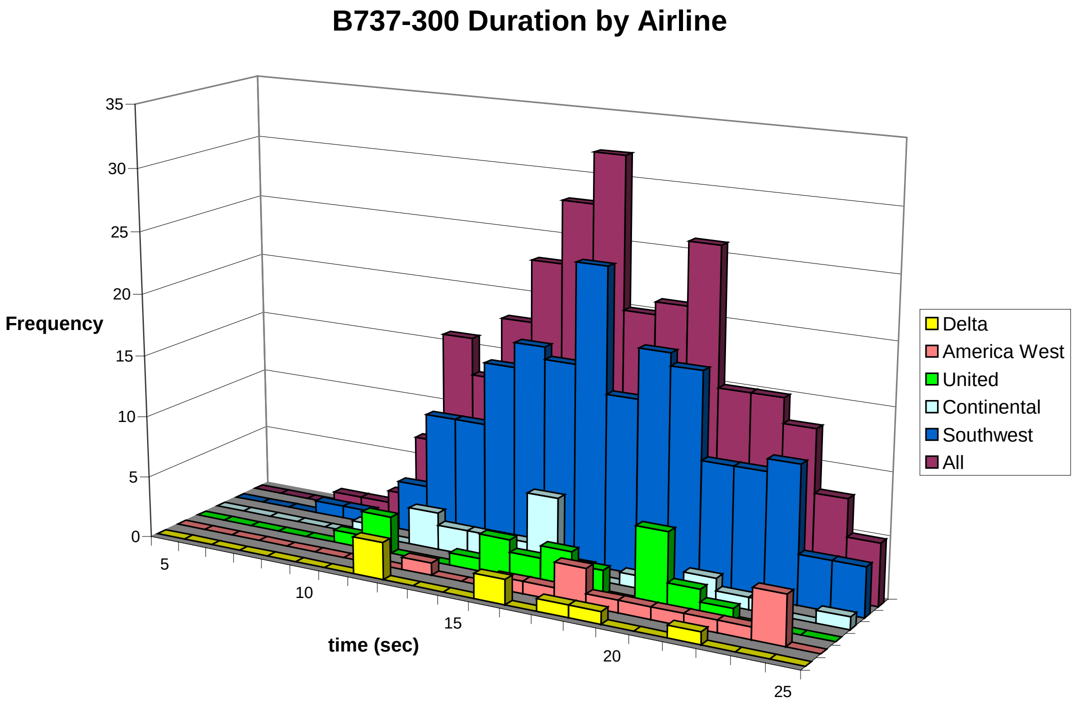


Figure 5-4

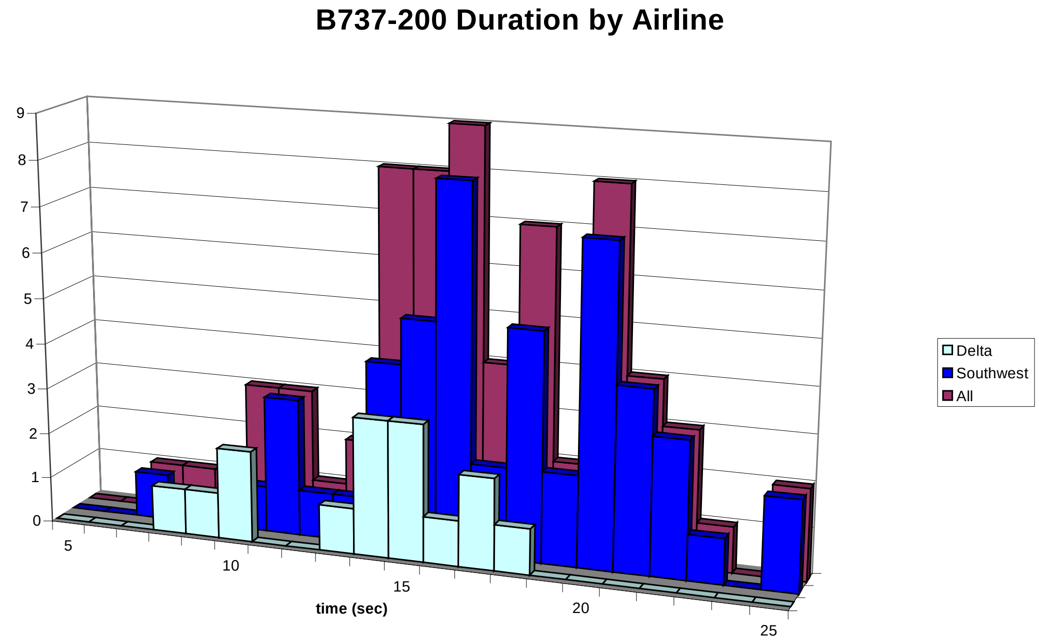


Figure 5-5

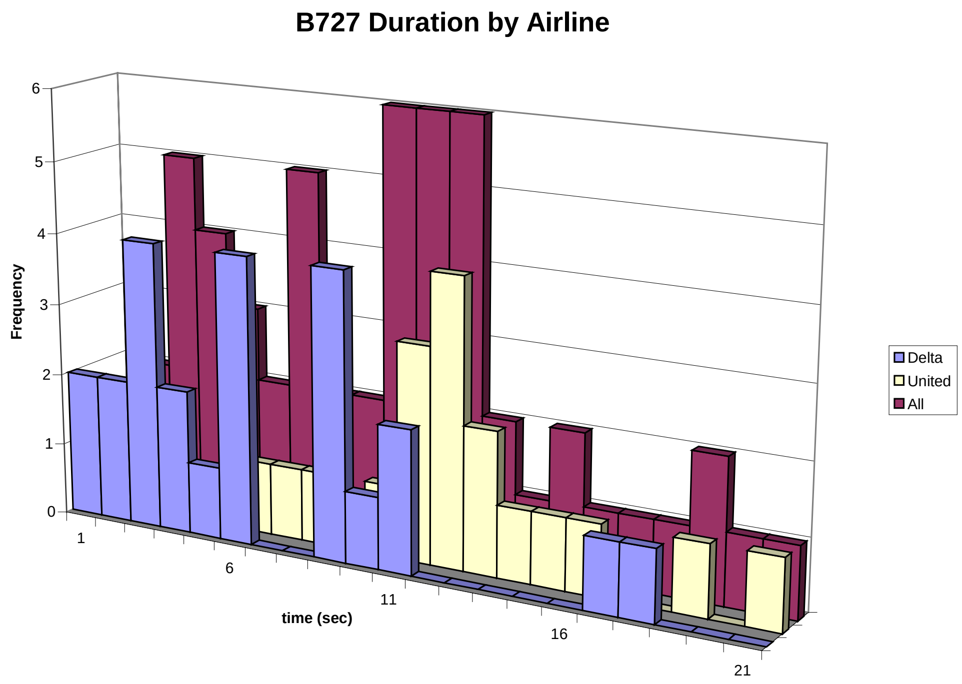


Figure 5-6

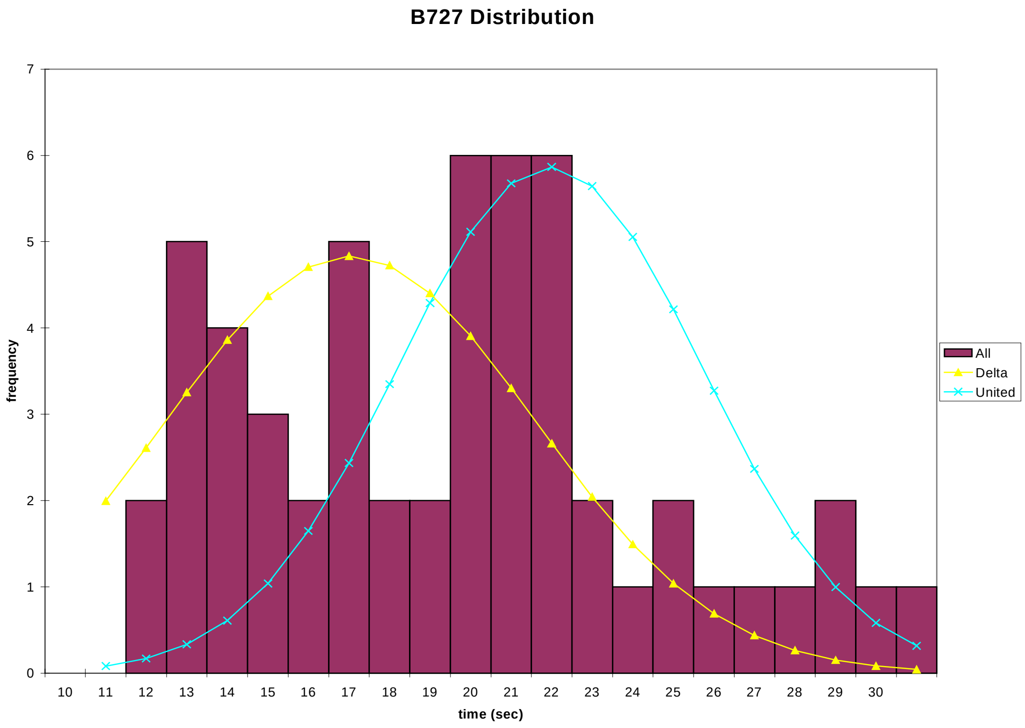


Figure 5-7

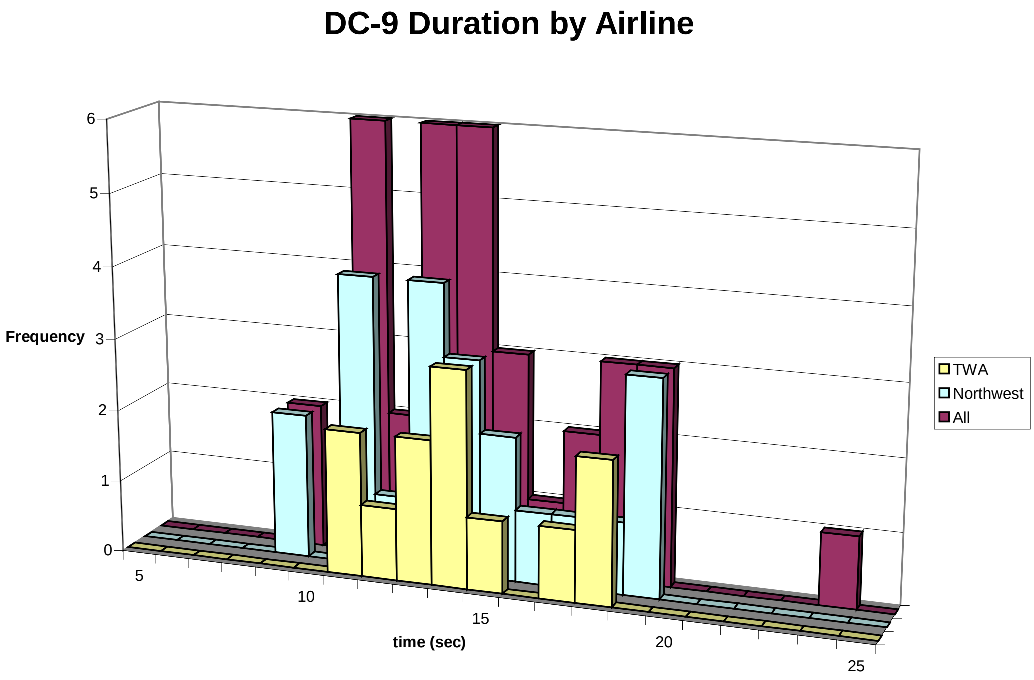


Figure 5-8

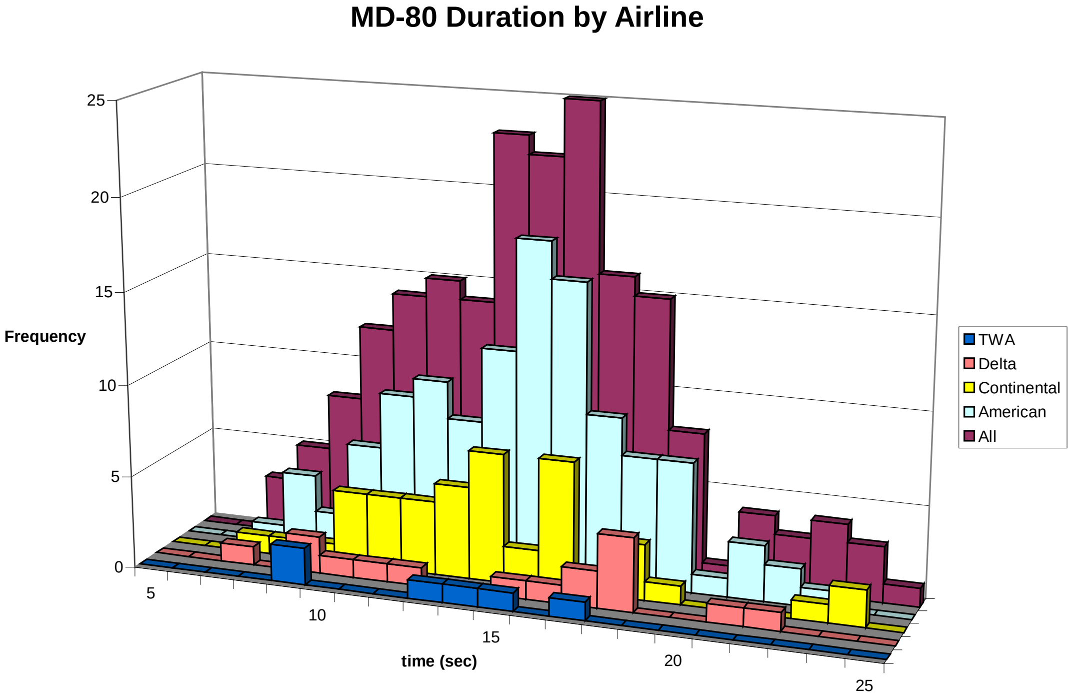


Figure 5-9

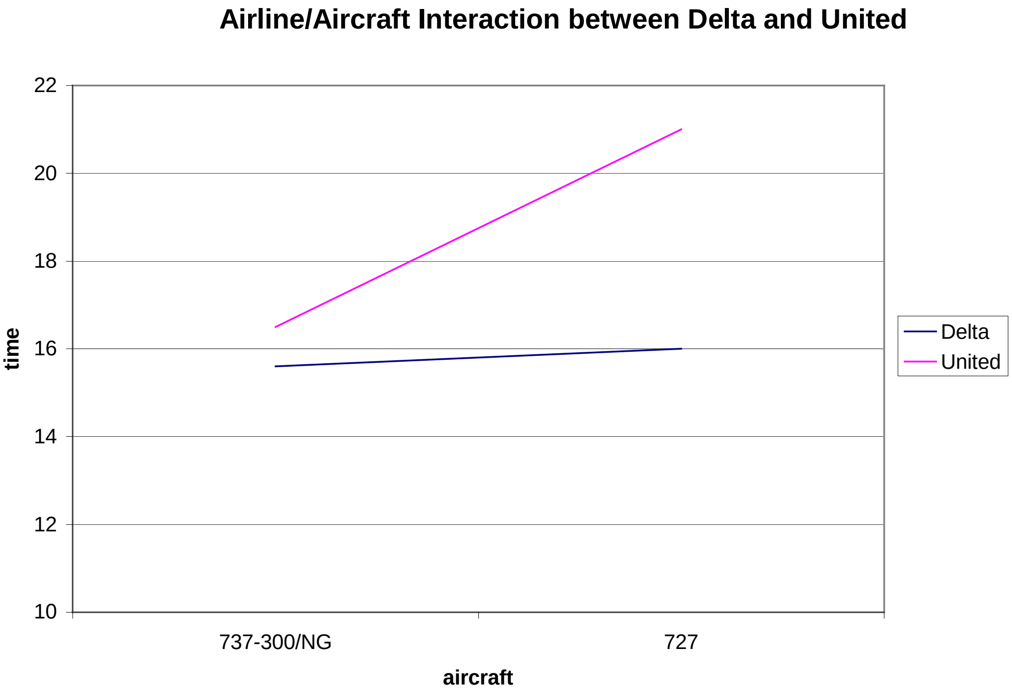
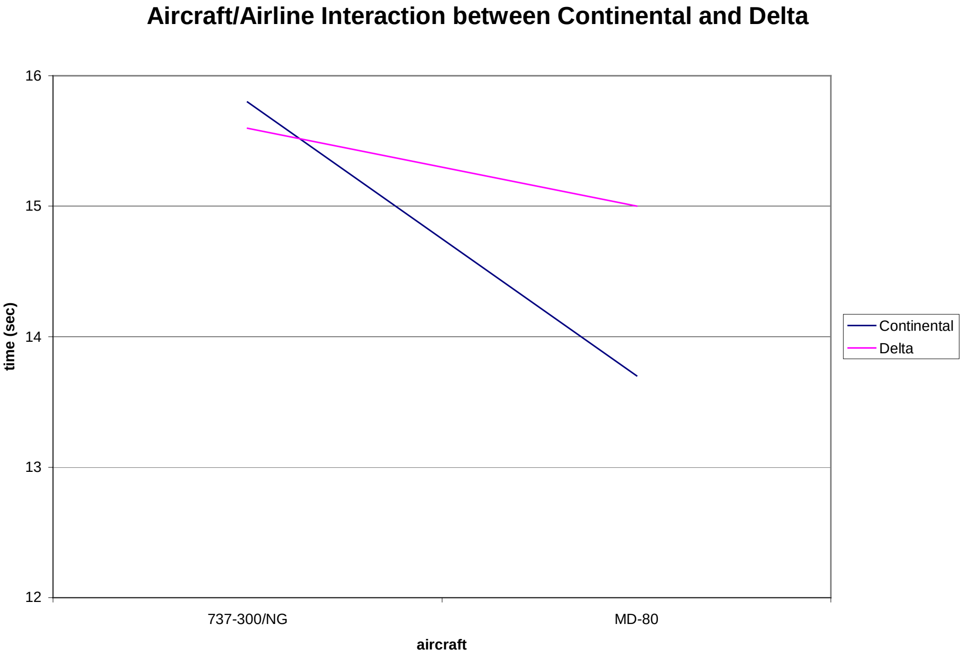


Figure 5-10



5.1.2 Analysis of Variance

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 the analysis of variance, a two factor fixed-effects model, similar to the following is used:

$$y_{ijn} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijn} \qquad (5\text{-}1)$$

where:

y_{ijn} = observation *n* in cell *ij*
μ = overall mean
τ_i = effect of aircraft type *i*
β_j = effect of airline *j*
$(\tau\beta)_{ij}$ = effect of the interaction between aircraft *i* and airline *j*
ε_{ijn} = random error component

When the data is balanced, sum of squares are computed as follows (Montgomery, 1997):

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{n=1}^{n} y_{ijn}^2 - \frac{y_{...}^2}{abn} \qquad (5\text{-}2)$$

$$SS_A = \frac{1}{bn}\sum_{i=1}^{i} y_{i..}^2 - \frac{y_{...}^2}{abn} \qquad (5\text{-}3)$$

$$SS_B = \frac{1}{an}\sum_{j=1}^{b} y_{.j.}^2 - \frac{y_{...}^2}{abn} \qquad (5\text{-}4)$$

$$SS_{AB} = \frac{1}{n}\sum_{i=1}^{a}\sum_{j=1}^{b} y_{ij.}^{2} - \frac{y_{...}^{2}}{abn} - SS_A - SS_B \qquad (5\text{-}5)$$

$$\mathrm{SS_E} = SS_T - SS_A - SS_B - SS_{AB} \qquad (5\text{-}6)$$

where:

$$y_{...} = \sum_{ijn} y \text{, } \nabla \text{ i,j,n} \qquad (5\text{-}7)$$

SS_T = total sum of squares
SS_A = sum of squares between aircraft
SS_B = sum of squares between airlines
SS_{AB} = sum of squares due to aircraft/airline interactions
SS_E = sum of squares due to error

Mean squares (MS) are computed by dividing the sum of squares by the degrees of freedom.

$$MS_A = \frac{SS_A}{a-1}$$

When performing multi-factor ANOVA with empty cells, where all treatment-block (aircraft-airline) combinations are not represented, the sum of squares must be adjusted to separate the treatment and block effects. In this case, this adjustment is necessary because each aircraft type is operated by different combinations of airlines (Montgomery, 1997). Total sum of squares is now computed using the adjusted sum of squares for the aircraft effects. When each block contains the same number of treatments, the adjusted treatment sum of squares is shown in equation 5-8.

$$SS_{A(adj)} = \frac{k\sum_{i=1}^{a} Q_i^2}{\lambda a} \qquad (5\text{-}8)$$

where:

Q_i = adjusted total for treatment *i*,
k = number of treatments contained by each block
r = number of blocks contained by each treatment
λ = r(k-1)/(a-1)

Q_i is computed in equation 5-9:

$$Q_i = y_{i.} - \frac{1}{k}\sum_{j=1}^{b} n_{ij} y_{.j} \qquad (5\text{-}9)$$

After the model is fitted and the sum of squares are computed, the equality of the treatment effects are tested using the following null hypotheses:

$H_0 : \tau_1 = \tau_2 = \ldots = \tau_a = 0$ (5-10a)
$H_0 : \beta_1 = \beta_2 = \ldots = \beta_b = 0$ (5-10b)
$H_0 : (\tau\beta)_{ij} = 0, \nabla$ i,j (5-10c)

The test statistic is computed by equation 5-11 and is compared with the value $F_{\alpha,a-1,N-a}$.

$$F_0 = \frac{MS_{Aircraft(adj)}}{MS_E} \qquad (5\text{-}11)$$

If $F_0 > F$, then the null hypothesis is rejected. Rejecting H_0 in 5-10a would indicate that there are significant differences among aircraft types and that aircraft type is a factor which influences thrust reverse usage. Rejecting the null hypothesis in 5-10b would indicate that there are significant differences among airlines and that airline influences thrust reverse usage. Rejecting the null hypothesis in 5-10c indicates that there is interaction between airline and aircraft types.

The above equations are only valid when analyzing balanced data. The data is balanced only when there are an equal number of observations for each cell. Sometimes, unbalanced data results when it is not possible to obtain an equal number of observations. With unbalanced designs, the usual analysis of variance techniques are modified and the sum of squares are not orthogonal. ANOVA for unbalanced data is more difficult, particularly with empty cells. As discussed earlier, an *empty cell* is defined as an aircraft-airline combination where the number of observations $n_{ij} = 0$.

There are many methods available to analyze unbalanced data. Selecting the best method depends on the number of missing observations and empty cells. If only a few observations are missing, it may be easy to estimate missing observations, based on the cell averages. If a few cells contain extra observations, it may be easy to simply eliminate the extra observations to create balanced data. For the method of unweighted means, ANOVA is performed on the cell averages. All of these procedures result in an approximate analysis and cannot be used on data with empty cells (Montgomery, 1997).

When empty cells are present or when the data is severely unbalanced, a regression model can be used. A regression model is developed, a model is fit to the data, and a regression significance approach is tested. The results of the regression are used to predict the missing values. With the missing values added, the data becomes balanced. The sum of squares can be computed normally and then partitioned. SAS software uses the regression method in PROC GLM.

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_0	P-Value
Aircraft	1406.2	5	281.2	17.96	<0.001
Error	10161.7	649	15.7		
Total	11567.9	654			

F_0 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_0 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_0	$F_{0.05,v1,v2}$
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_0 is greater than $F_{\alpha,v1,v2}$ 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	σ
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	$F_{0.05,v1,v2}$
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	σ
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_0	$F_{0.05,v1,v2}$
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	μ	σ	t_0	$t_{.025,n1+n2-2}$	result
B727-200	Delta	24	16.04	4.54	-3.74	2.02	reject H_0
	United	18	20.96	3.74			
B737-200	Delta	15	13.29	3.04	-3.10	2.00	reject H_0
	Southwest	50	16.73	3.96			
DC-9	Northwest	22	13.47	3.00	0.11	2.04	accept H_0
	TWA	12	13.58	2.45			

In order to exhaust all possible uses of the collected data, it was decided to examine the effect of runway use on thrust reverse usage. The exit configuration for a runway heavily influences landing distance and runway occupancy time; it may also influence thrust reverse usage time. ABIA's two runways have distinctly different exit types. The newer, east runway has high-speed angled exits, while the west runway has right-angled exits. Aircraft can exit the runway sooner with an angled exit, but must slow to a near stop to use a right-angle exit. On the east runway, high speed exits are located at 6,700 feet from each landing end. On the west runway, right-angle exits are located at 5,250 and 7,000 feet from each landing end.

On the west runway, most aircraft use the second exit, located 7,000 feet down the runway. Occasionally some aircraft are able to take the first exit. On the east runway, virtually all commercial aircraft use the high-speed exit. If the high-speed exit is missed on the east runway, taxiing to the end and doubling back is approximately 1 mile. If the second exit is missed on the west runway, the aircraft may have to taxi all the way to the end and back, a distance of two miles. Hence, there is an incentive to not to miss the second exit.

In order to examine the effect of runway on reverse thrust usage, a cross-tabulation of aircraft-airline groups and runway is shown in Table 5-9. The distribution of reverse thrust usage for each runway is shown in Figure 5-11. According to the cross-tabulation, there appears to be interaction between aircraft-airline combinations and runway. For example, thrust reverse usage for American MD-80s varies significantly, from 13 seconds when landing on 17L to nearly 15 seconds when landing on 35L. For Continental MD-80s, usage does not vary significantly according by runway. In Tables 5-10 and 5-11, the observations are grouped and coded by aircraft/airline abbreviations shown in Table 5-9.

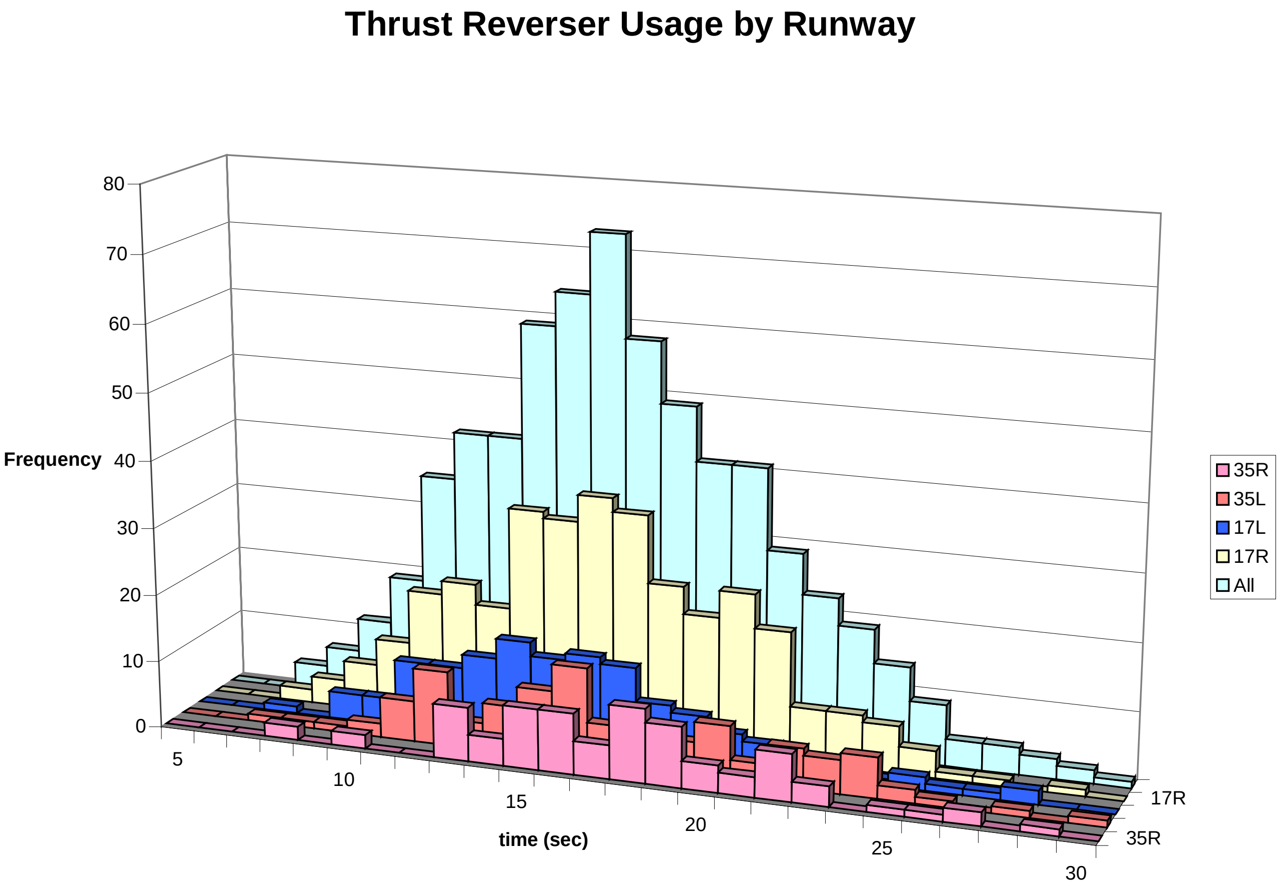
Table 5-9 Aircraft/Airline Abbreviations

Airline Code	Airline	Aircraft Code	Aircraft
AA	American	733	B737-300/NG
CO	Continental	737	B737-200
DL	Delta	757	B757
HP	America West	DC-9	DC-9
NW	Northwest	M80	MD-80
SW	Southwest	727	B727
TW	TWA		
UA	United		

Table 5-10 Aircraft-Airline vs. Runway

	East Runway		West Runway		All
	17L	35R	17R	35L	
CO733	0 --	1 13	16 15.323	6 17.667	23 15.834
DL733	0 --	1 18.6	3 16.367	4 14.175	8 15.55
HP733	0 --	0 --	10 18.32	5 21.98	15 19.54
SW733	41 17.147	28 18.708	86 16.702	34 17.297	189 17.203
UA733	1 20.5	0 --	17 16.662	6 15.267	24 16.473
DL737	7 14.4	4 12.85	4 11.8	0 --	15 13.293
SW737	10 17.91	9 18.656	25 16.103	6 14.517	50 16.734
AA757	3 13.833	1 14.3	15 14.273	9 13.056	28 13.836
DL727	13 15.797	5 15.42	2 16.137	4 17.525	24 16.035
UA727	0 --	0 --	12 19.942	6 23	18 20.961
NWDC9	15 13.263	4 15.6	3 11.667	0 --	22 13.47
TWDC9	10 13.545	1 14.4	1 13.1	0 --	12 13.579
AAMD80	15 12.955	18 15.272	74 14.199	10 14.93	117 14.267
COMD80	5 13.08	0 --	31 13.979	8 13.037	44 13.706
DLMD80	8 11.495	3 21.182	4 18.35	2 13.4	17 15.041
TWMD80	2 15.35	1 12.3	2 10.75	1 9.0	6 12.25
All	130 15.131	76 17.022	305 15.605	101 16.380	612 15.808

Figure 5-11

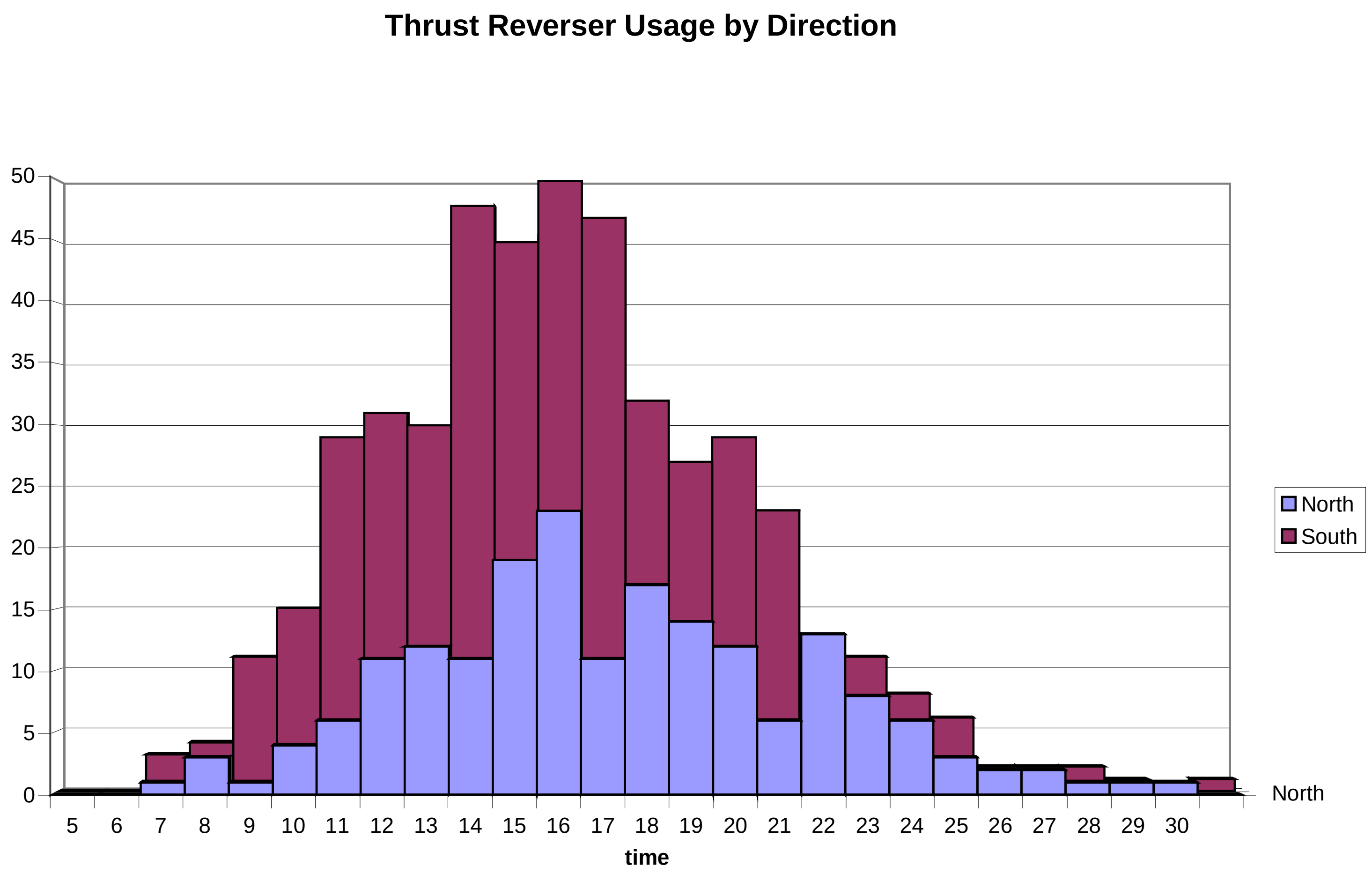

Thrust Reverser Usage by Runway
Frequency
0
10
20
30
40
50
60
70
80
5
10
15
20
25
30
time (sec)
17R
35R
35R
35L
17L
17R
All

Next, a different cross-tabulation was performed to compare the effect of south flow and north flow on thrust reverse usage. Runways are numbered according to their magnetic heading of aircraft direction of travel, rounded to the nearest 10°. Runways 17L and 17R are oriented at a heading of approximately 170 degrees. For the opposite direction of travel on the same runway, 180 degrees is added to the runway heading. Parallel runways are labeled “L” for left, “C” for center and “R” for right. At ABIA, the east runway is 17L-35R and the west runway is 17R-35L. South flow is defined as landing and taking off towards the south, on runways 17L and 17R. North flow is operating towards the north on runways 35L and 35R. Table 5-11 shows the cross-tabulation of aircraft-airline combination with direction: Figure 5-12 shows the distribution of reverse thrust usage according to direction:

Table 5-11 Aircraft-Airline vs. Direction

	South	North	All
CO733	16 15.323	7 17	23 15.834
DL733	3 16.367	5 15.06	8 15.55
HP733	10 18.32	5 21.98	15 19.54
SW733	127 16.846	62 17.934	189 17.203
UA733	18 16.876	6 15.267	24 16.473
DL737	11 13.455	4 12.85	15 13.293
SW737	35 16.619	15 17	50 16.734
AA757	18 14.2	10 13.18	28 13.836
DL727	15 15.842	9 16.356	24 16.035
UA727	12 19.942	6 23	18 20.961
NWDC9	18 12.997	4 15.6	22 13.47
TWDC9	11 13.504	1 14.4	12 13.579
AAM80	89 13.989	28 15.15	117 14.267
COM80	36 13.854	8 13.037	44 13.706
DLM80	12 13.78	5 18.069	17 15.041
TWM80	4 13.05	2 10.65	6 12.25
All	435 15.464	177 16.656	612 15.808

Figure 5-12


Thrust Reverser Usage by Direction
50
45
40
35
30
25
20
15
10
5
0
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
time
North
North
South

Reverse thrust usage appears to be slighter longer more during north flow. Average usage increased from 15.5 seconds during south flow to 16.7 seconds during north flow. Under north flow, the Taxiway G runway exits provide the quickest access to the terminal ramp. When landing to the north, taking the Taxiway G runway exits provide approximately 7,000 feet of landing length for both runways. As a result, it becomes the preferred exit.

It was also noticed that runway traffic is more evenly distributed between the east and west runways under north flow. This also reflects the availability and convenience of the Taxiway G exit. During north flow, reverse thrust for all aircraft-airline combinations increased for 10 of the 16 pairs exhibited in Table 5-11. Delta MD-80s observed the largest increase, of more than 4 seconds. A t-test was conducted to test the significance of the difference between the directional means. The test statistic t_0 was computed to be 3.35. At a 95% confidence interval $t_{.025,\infty} =$ 1.96. Therefore, it can be concluded that the overall difference between directions is significant.

After learning that runway could have a possible effect on thrust reverser usage, three-way analysis of variance was performed. A three-factor fixed-effects model, similar to the following is used:

$$y_{ijkn} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + \varepsilon_{ijkn} \qquad (5\text{-}12)$$

When runway is added to the model and the combination of interactions between the variables are compared, runway by itself becomes insignificant. This is thought to occur because of the lack of observations for some aircraft-airline-runway combinations. When runways are grouped by direction, they become marginally significant, along with the interaction between aircraft, airline, and direction. This is shown in Tables 5-12 and 5-13.

Table 5-12 Three-way ANOVA with Runway

Source of Variation	SS	df	MS	F_0	$F_{0.05,v1,v2}$	Significant
Aircraft	239.4	5	47.8	3.71	2.21	Yes
Airline	449.3	7	64.2	4.97	2.01	Yes
Runway	43.6	3	14.5	1.13	2.60	No
Aircraft*airline	153.0	3	51.0	3.95	2.60	Yes
Aircraft*rwy	368.1	14	29.3	2.04	1.71	Yes
airline*rwy	335.9	17	19.8	1.53	1.64	Marginal
acft*airline*rwy	2.3	3	0.8	0.06	2.60	No

Table 5-13 Three-way ANOVA with Direction

Source of Variation	SS	df	MS	F_0	$F_{0.05,v1,v2}$	Significant
aircraft	255.6	5	51.1	3.87	2.21	Yes
airline	421.5	7	60.2	4.55	2.01	Yes
direction	32.5	1	32.5	2.46	3.84	No
aircraft*airline	211.1	3	70.4	5.32	2.60	Yes
aircraft*dir	67.8	5	13.6	1.03	2.21	No
airline*dir	69.4	7	9.9	0.75	2.01	No
acft*airline*dir	100.9	3	33.6	2.54	2.60	Marginal

5.1.3 Headwind Analysis

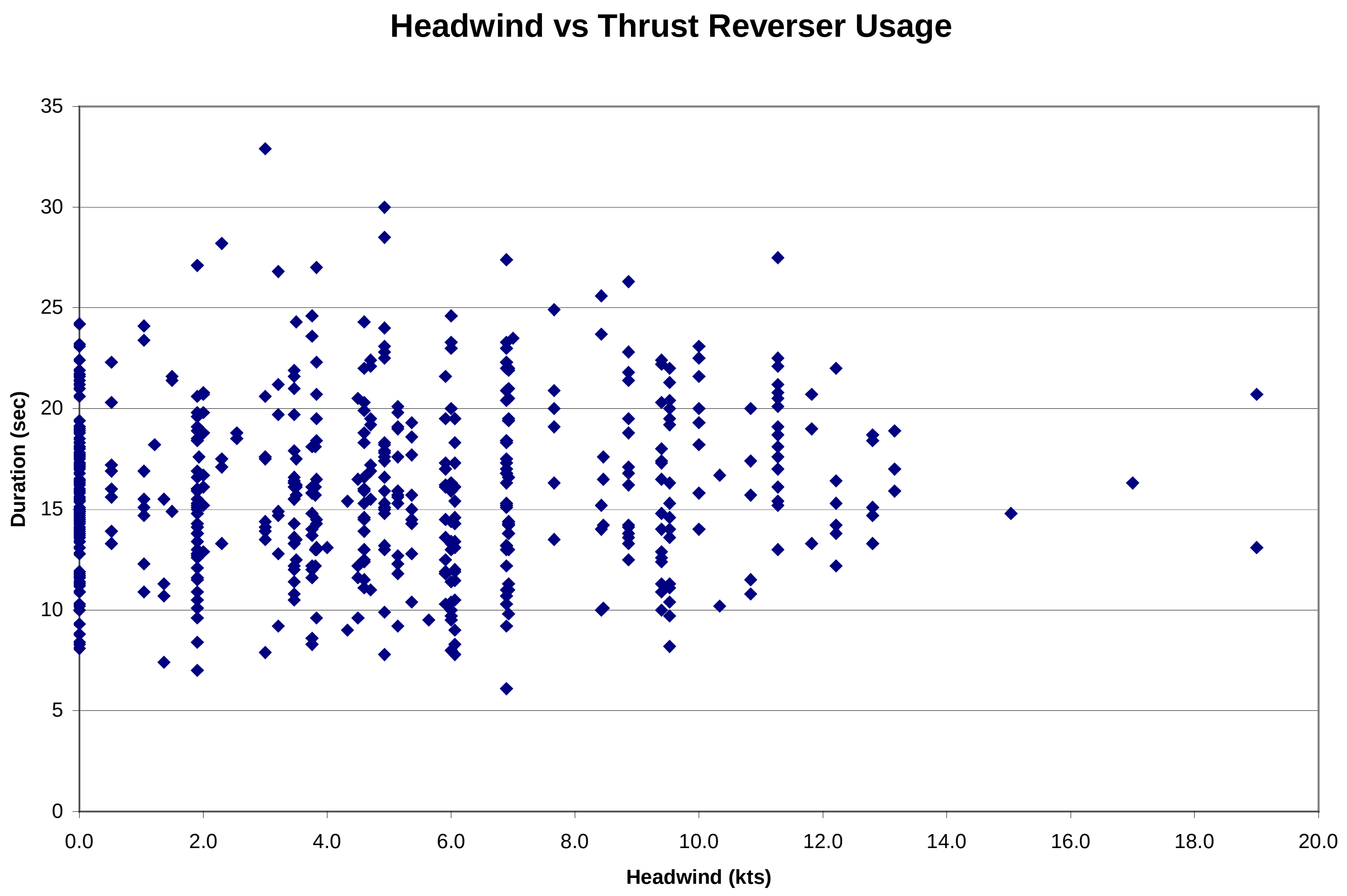
To minimize landing and takeoff distances, aircraft typically land and takeoff into the direction of the wind, as much as possible. In airport design, runways are laid out according to maximize the use of the prevailing headwinds, while minimizing the effect of crosswinds. Wind is a vector which can be broken down into a headwind component and a crosswind component. Flying into a headwind increases an aircraft’s airspeed and lift while flying into a tailwind decreases the relative airspeed and lift. Crosswinds have a minimal affect on lift, but can limit the ability of the aircraft to land while maintaining a track with the runway alignment. Since headwinds can result in increased lift and drag, it is thought that wind speed could possibly have an impact on thrust reverser usage.

To determine the effect of wind on thrust reverser usage, wind data was gathered for ABIA from the National Climatic Data Center archives (NCDC, 2000). The NCDC data provides hourly measurements of windspeed and direction. Using the runway heading and the wind direction, the headwind component was computed for each hour of data collected and this value was added to the data observations.

When the wind direction was reported by the NCDC as “variable”, an expression to compute the headwind velocity was derived by computing the average resultant headwind as the wind direction changes a total of 180 degrees, in 10 degree increments. For example, if variable winds at 5 mph were recorded during south flow, the headwind component was computed in 10 degree increments, starting from a heading of 80 degrees to a heading of 260 degrees. The average headwind velocity component was found to be approximately 0.635 of the windspeed.

A plot of headwind and thrust reverser usage is shown in Figure 5-13. As shown by the data, headwind has very little impact on thrust reverser usage. A correlation coefficient of 0.09 indicates very little relation between headwind and thrust reverse usage. The wind data compiled by the NCDC is the hourly average of the actual windspeed and direction. The instantaneous windspeed and direction are needed to conduct a more accurate analysis. This could possibly explain the lack of correlation found between windspeed and thrust reverser usage.

Figure 5-13


Headwind vs Thrust Reverser Usage
Duration (sec)
35
30
25
20
15
10
5
0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Headwind (kts)

5.1.4 Comparison of Cascade and Clamshell Thrust Reversers

As previously discussed, clamshell thrust reversers are more effective than cascade reversers. With clamshell thrust reversers, clamshell buckets are placed into the airflow completely behind the engine. With cascade reversers, only the airflow from the fan is reversed, through a series of openings in the engine nacelle. Clamshell thrust reversers divert between 30-40% of the engine thrust forward, while cascade reversers reverse 15-20%. Since clamshell reversers are more effective, they produce more braking action during landing and are used less. Table 5-14 shows a comparison between cascade and clamshell reversers. Because of their similarity of design, the MD-80 and DC-9 were grouped together.

Table 5-14 Comparison of Thrust Reverser Usage by Type

Type	Aircraft	Duration	Average
Cascade	B737-300	17.1	16.4
	B757	13.8	
	B727	18.4	
Clamshell	B737-200	16.1	15.1
	DC-9/MD-80	14.1	

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. Figure 5-14 shows the distribution of reverse thrust usage during power-backing. As expected, the distribution is near normal.

Figure 5-14

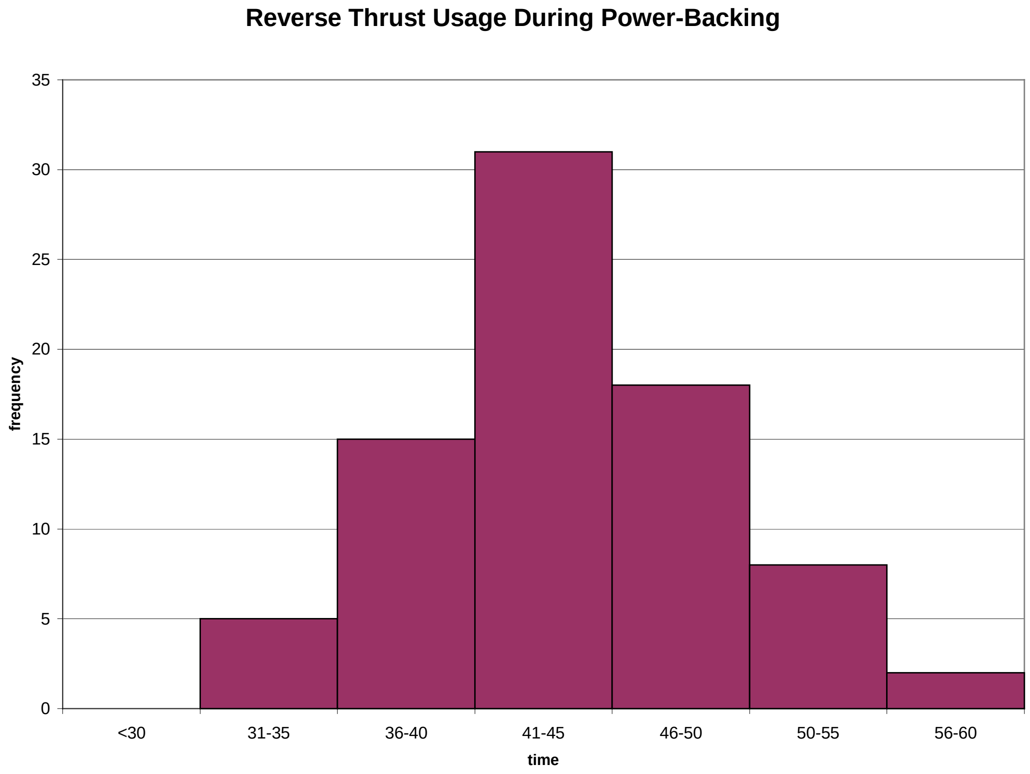


Table 5-15 Power-backs By Gate

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 power-backs 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.

6.0 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 NOx 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.

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 section 5.1.4, 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

6.2.1 Determination of Engine Power-Setting

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 2.7, 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.

Using simple physics, it can be shown that a power-setting of 80% is needed to maintain motion during backing. In the physics of motion, enough force is needed to overcome the rolling static friction, to begin movement, and rolling kinetic friction, to maintain movement. A typical takeoff weight for an MD-80 is 130,000 lbs or 58,000 kg. A typical coefficient for rolling kinetic friction is 0.1. The frictional force is directly related with the normal force and is shown in Equation 6-1.

$$f = \mu_k N \qquad (6\text{-}1)$$

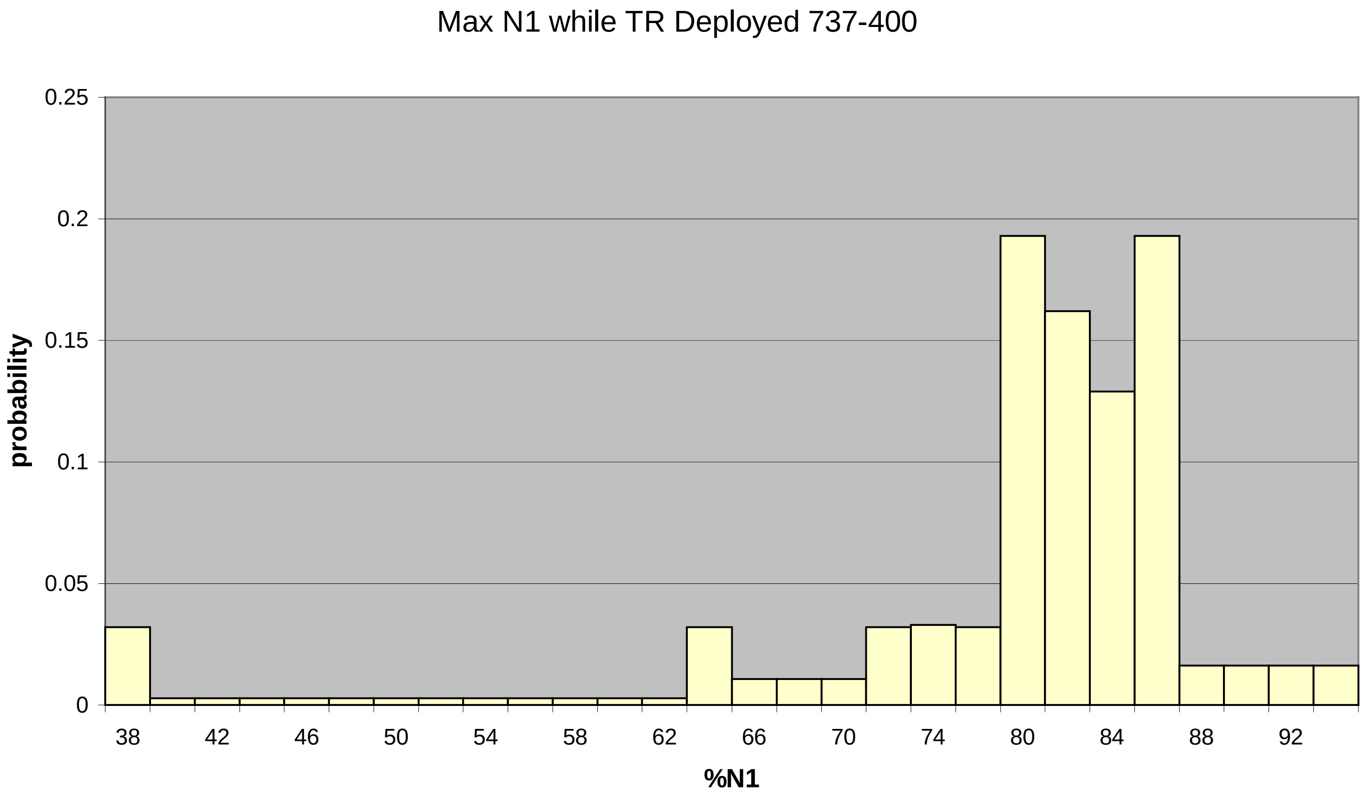
where:

$\mu_k = 0.1$
$N = mg = (58984 \text{ kg}) \text{x} (9.8 \text{ m/s}^2) = 578.0 \text{ kN}$

The resulting frictional force is equal to 57.8 kN, which must be overcome by the engines to maintain motion. Using the conversion of 4.445 kN per 1,000 lbs of thrust, this amount of force is equivalent to 13,000 lbs of reverse thrust. The MD-80 uses

Pratt & Whitney JT8D-217 engines, which produce a total of 40,000 lbs of thrust in the forward direction. If the reversers are 40% effective, then a power setting of 80% is necessary to produce this amount of reverse thrust.

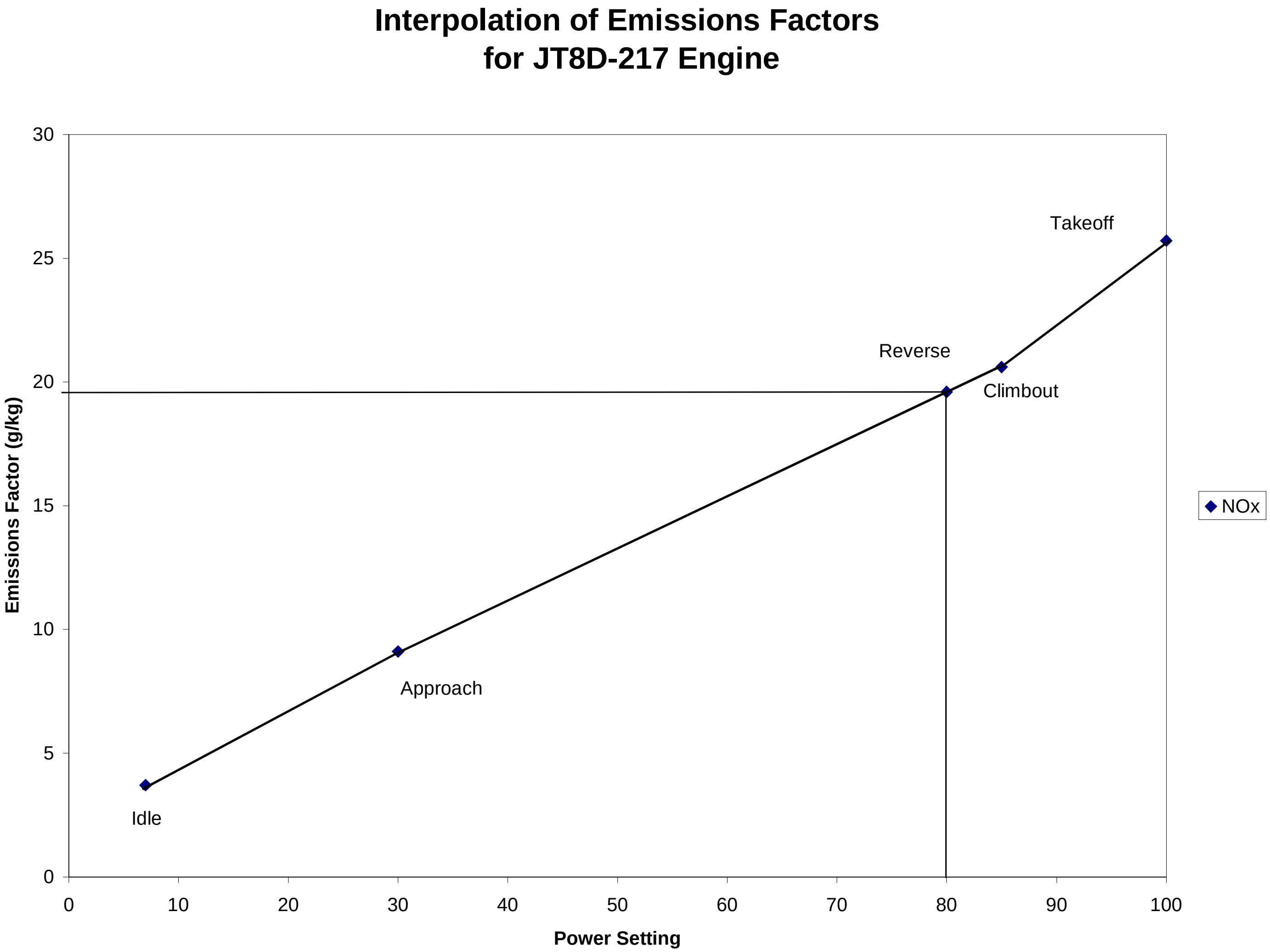
Figure 6-1


Max N1 while TR Deployed 737-400
probability
0.25
0.2
0.15
0.1
0.05
0
38
42
46
50
54
58
62
66
70
74
80
84
88
92
%N1

6.2.2 Interpolation of Emissions Factors

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 NOx emissions factors for the JT8D-217 engine, used on the MD-80. The NOx 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 NOx emissions factor of 19.6 g/kg for the MD-80.

Figure 6-2


Interpolation of Emissions Factors
for JT8D-217 Engine
Emissions Factor (g/kg)
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
Power Setting
Takeoff
Reverse
Climbout
Approach
Idle
◆ NOx

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.

6.4.1 Emissions during Landing

Detailed spreadsheets showing the emissions computations for reverse thrust during landing are included in the Appendix. 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

6.4.2 Emissions during Power-Backing

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

	Emissions kg/LTO		
Source	CO	HC	NOx
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.

6.4.3 Total Reverse Thrust Emissions

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 NOx 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 NOx emissions from reverse thrust at Austin and DFW. In 2007, the proportion of NOx 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.

7.0 AIR QUALITY EFFECT OF REVERSE THRUST

This chapter evaluates the effect of emissions produced from reverse thrust on air quality in the Dallas/Ft. Worth Metropolitan Area. The significance of ozone as an air pollutant as well as its health effects are discussed. Federal clean air standards for ozone and background on ozone chemistry are covered. An analysis of the Dallas air quality during Summer 2001 is presented, with an emphasis on the recently opened Continuous Air Monitoring Station (CAMS) 70. Finally, this chapter summarizes the air quality modeling results and discusses the airport's impact on nitrogen dioxide levels.

7.1 Ozone as a Pollutant

Ozone (O_3) 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, NOx, 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).

A new standard was developed by the EPA in 1997 for ozone, known as the eight-hour standard. It requires daily averaging of eight consecutive hours of ozone readings. A region is declared to be in violation if the 3 year average of the fourth highest eight-hour averages at a single monitor in the region exceed 0.08 parts per million (85 parts per billion). The previous one-hour standard of 0.12 ppm (125 ppb) standard still applies to communities that were not in attainment of that standard in July 1997. Once these communities meet the one-hour standard, the EPA will assess them by the new eight-hour standard. For the eight hour standard, three full years of data were needed to enforce the standard. New attainment assessments were made beginning Fall 2000.

7.2 Ozone Chemistry

Seinfeld and Pandis declare that ozone “can be considered as the principal product of tropospheric chemistry” and that “NOx is the key in the chemistry of the troposphere”. Formulas 7.1, 7.2 and 7.3 show the key reactions in ozone formation.

$$NO_2 + hv \rightarrow NO + O \qquad (7.1)$$

$$O + O_2 + M \rightarrow O_3 + M \qquad (7.2)$$

$$O_3 + NO \rightarrow NO_2 + O_2 \qquad (7.3)$$

In Formula 7.1, an oxygen atom is removed from NO_2 as a result of photolysis from sunlight. In Formula 7.2, the monatomic oxygen reacts with a normal O_2 molecule to form ozone. *M* represents a third molecule which absorbs the extra energy and stabilizes the ozone molecule which is formed. In Formula 7.3, ozone reacts with nitric oxide (NO) to regenerate NO_2. Under normal conditions, very little ozone accumulates, as the ozone produced in 7.2 reacts very quickly with NO in 7.3 (Seinfeld and Pandis, 1998).

Formula 7.3 is known as the “sink reaction”, since it keeps ozone from accumulating. VOC emissions interfere with 7.3 and prevent the accumulated ozone from being removed. This is shown in Formulas 7.4 through 7.6. In the following reactions, VOCs are designated as *R*.

$$RH + OH\cdot \rightarrow R\cdot + H_2O \qquad (7\text{-}4)$$

$$R\cdot + O_2 + M \rightarrow RO_2\cdot + M \qquad (7\text{-}5)$$

$$RO_2\cdot + NO \rightarrow RO\cdot + NO_2 \qquad (7\text{-}6)$$

In Formulas 7-4 through 7-6, the hydroxyl radical ($OH\cdot$) is a key component. Seinfeld and Pandis deem the hydroxyl radical as the “most important reactive species of the troposhere.” $OH\cdot$ is naturally occurring in the atmosphere and its formation is shown by Formulas 7-7 and 7-8.

$$O_3 + hv \rightarrow O(^1D) + O_2 \qquad (7\text{-}7)$$

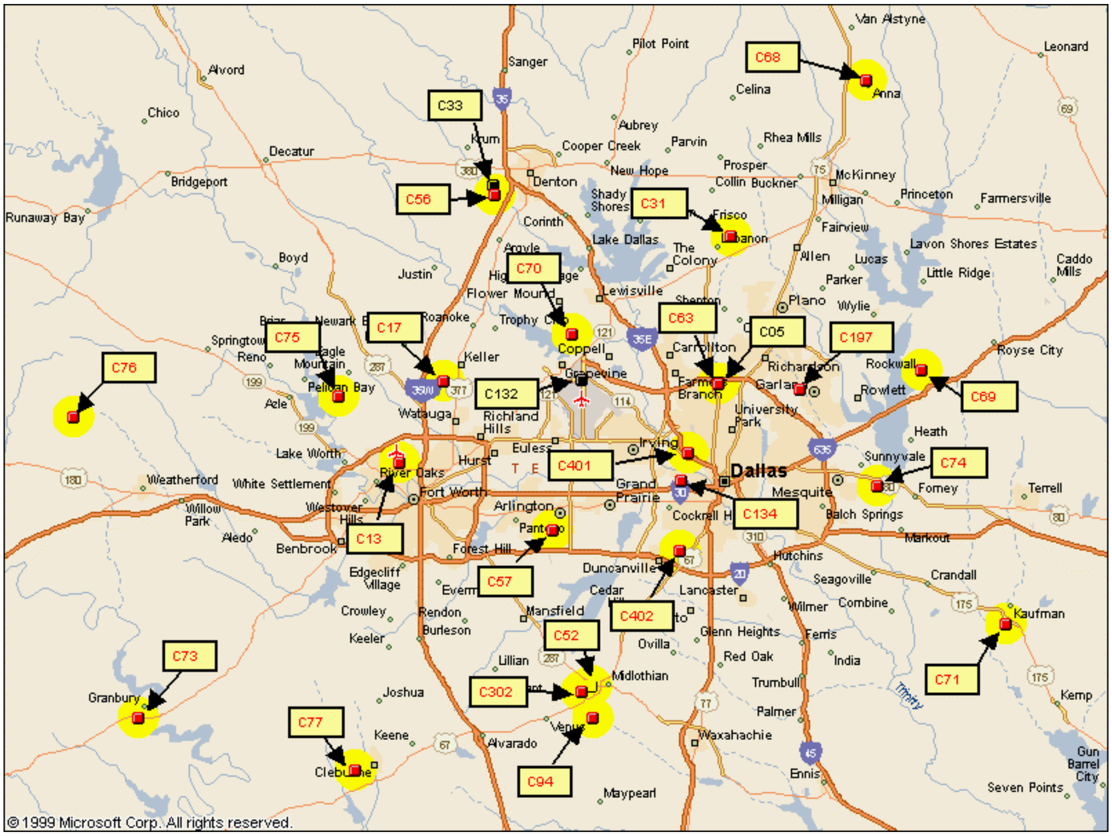
$$O(^1D) + H_2O \rightarrow 2\ OH\cdot \qquad (7\text{-}8)$$

In 7-7, O_3 is divided into an excited oxygen atom $O(^1D)$ and an oxygen molecule. $O(^1D)$ combines with a water molecule to form two hydroxyl radicals. In 7-4 and 7-5, the hydroxyl radicals react with the hydrocarbons (RH) to form peroxy radicals ($RO_2\cdot$) As shown in 7-6, nitric oxide reacts the peroxy radicals, instead of ozone in 7-3. As a result, the ozone produced in 7-2 is not removed and keeps forming.

7.3 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

Figure 7-1 Air Quality Monitoring Stations in Dallas Region



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 were above 85 ppb. For 2001, the fourth highest value of the 8-hour average at C70 is 97 ppb, which is nearly equal to the maximum fourth highest value for the region at C13 of 98 ppb.

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

Table 7-2 Eight-Hour High Values at Selected Dallas Area Stations

Monitoring Site	**Highest**			**Second Highest**			**Third Highest**			**Fourth Highest**		
	Date	**Time**	**Value**	**Date**	**Time**	**Value**	**Date**	**Time**	**Value**	**Date**	**Time**	**Value**
Frisco C31	6/20/01	900	**102**	8/19/01	1200	**98**	6/26/01	1000	**97**	6/18/01	1100	**92**
Dallas Hinton St. C401/C161	8/4/01	1100	**112**	8/19/01	1100	**92**	9/12/01	1100	**90**	7/14/01	1200	**88**
Denton Airport South C56	6/26/01	1000	**107**	8/4/01	1200	**103**	6/16/01	1100	**98**	8/3/01	1000	**97**
Granbury C73	8/6/01	1100	**98**	7/14/01	1200	**92**	9/12/01	1200	**90**	8/5/01	1200	**88**
Cleburne Airport C77	9/13/01	1000	**95**	8/6/01	1100	**95**	9/12/01	1100	**94**	8/5/01	1100	**93**
Parker County C76	8/3/01	1400	**107**	9/13/01	1200	**92**	8/4/01	1500	**89**	8/14/01	1200	**88**
Rockwall Heath C69	8/4/01	1100	**88**	6/19/01	900	81	8/15/01	1100	80	6/20/01	1000	**80**
Eagle Mountain Lake C75	8/4/01	1200	**112**	8/3/01	1100	**112**	8/14/01	1100	**105**	9/13/01	1000	**94**
Ft. Worth Northwest C13	8/4/01	1200	**116**	8/3/01	1100	**111**	9/13/01	1100	**106**	8/14/01	1100	**98**
Keller C17	8/4/01	1500	**125**	8/3/01	1000	**103**	8/14/01	1100	**102**	9/13/01	1100	**97**
Grapevine Fairway C70	8/4/01	1100	**112**	8/3/01	1100	**99**	6/26/01	1100	**97**	6/16/01	1100	**97**

7.4 Air Quality Modeling

7.4.1 Modeling Background

The EPA requires states to use photochemical grid models for air quality planning and to develop a state implementation plan for metropolitan areas that are not in attainment. The model contains three-dimensional meteorological and emissions data for a region, divided into thousands cubes, stacked on top of each other. Horizontal motion of the air is modeled, as well as vertical mixing. Emissions from point, area, mobile, and biogenic sources are included. The model predicts ozone concentrations based on the amount of ozone precursors and solar radiation, using the chemical reactions previously presented (TNRCC Modeling, 2001).

To develop a model, a series of days is chosen, when high levels of ozone were recorded. This is known as an “ozone episode”. Weather data during this episode is obtained along with area emissions data. The model is run and the results are compared with the real data recorded. When the model results are validated, estimates of future emissions are used to develop a “future case”. Economic forecasts are used to predict the future growth of population, automobile traffic, and industry. Future emissions are predicted using the rate of growth and future control strategies which are proposed to be implemented. The model is run again with the future emissions to determine the effectiveness of the control strategies in reducing ozone levels.

7.4.2 Selection of an Episode for 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 7-3 shows the maximum observed ozone concentrations and the simulated maximum using the 1995 base case on each date.

Table 7-3 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 NOx 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 NOx water heaters
- Electrification of Airport GSE

Table 7-4 shows a comparison of the emissions from 2007d Future Base and Strategy D30. Table 7-5 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 7-4 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

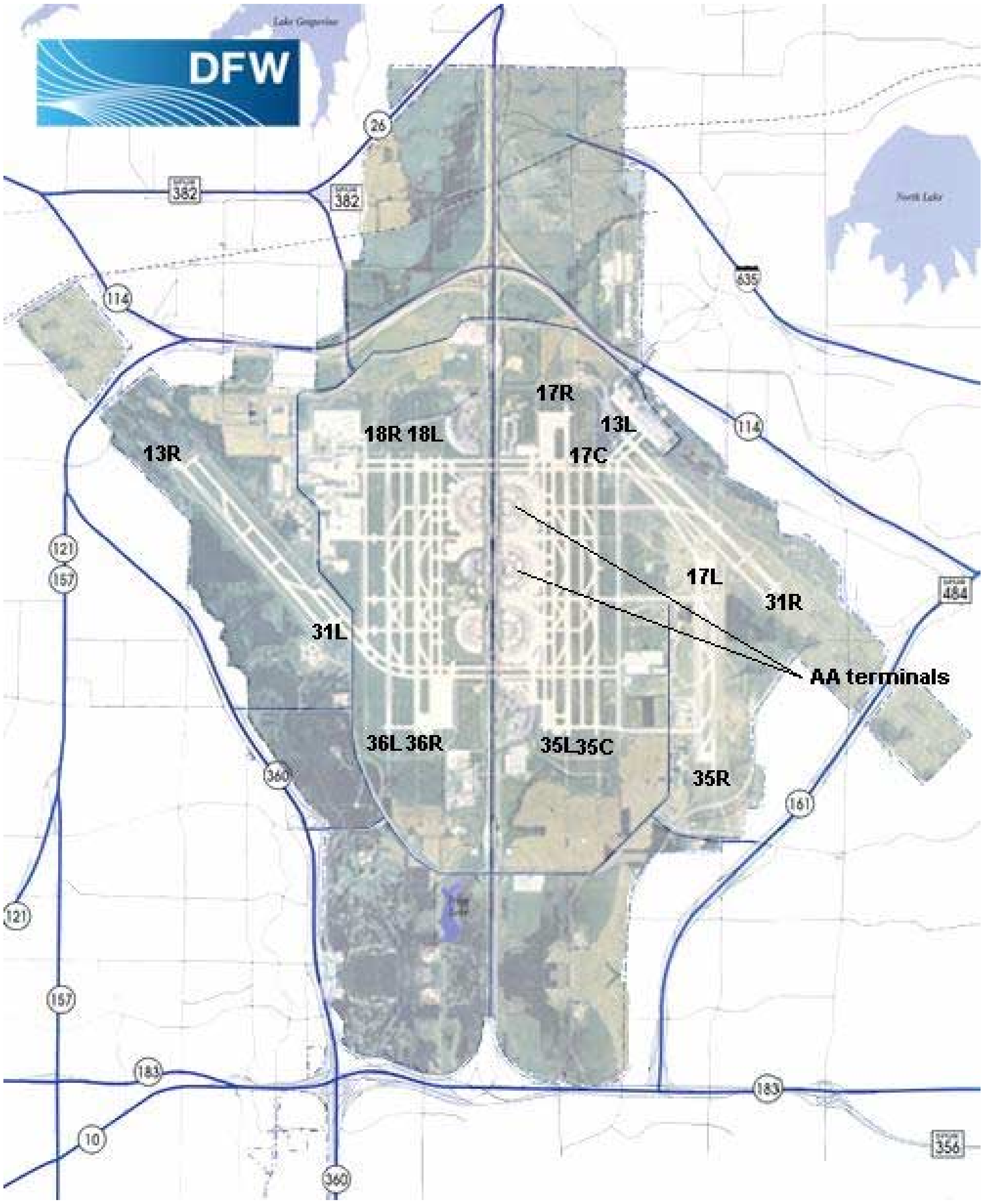
Table 7-5 2007 Ozone Predictions

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.

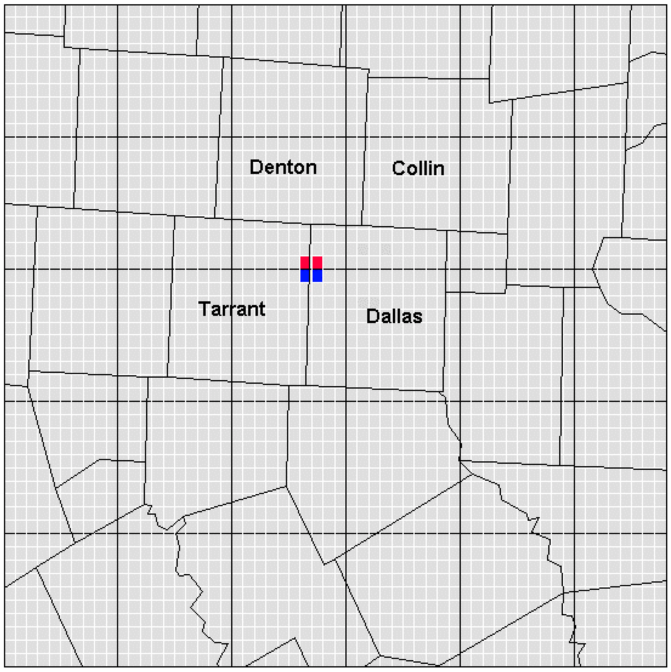
As previously discussed, current airport emissions inventories do not include emissions produced from reverse thrust. Reverse thrust is responsible for 1.2 tons per day of NOx emissions at DFW Airport. In order to simulate the effect of emissions from reverse thrust, the additional NOx must be added 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^2, 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



7.4.3 Development of a Masking Factor

To add the emissions from reverse thrust, a masking factor was applied to the affected grid cells. Since the vast majority of NOx 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 NOx 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 results is concentrated at ground level at the north end of the airport. Table 7-6 shows NOx emissions 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 7-6 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 7-7 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 7-7 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

7.4.4 Modeling Results

Next, the CAMx run was started, which took approximately 3 hours to complete on a DEC 433 Unix Workstation. 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_3 tile plots, there is a distinct reduction in ozone levels near the airport, due to

NOx scavenging. The prevalence of NOx scavenging near the airport is even more pronounced at 19:00. This will be discussed in further detail in section 7.5. 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 7-9 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 7-10 shows the difference in values of ozone concentrations resulting from the use of reverse thrust. As a result of NOx 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_2. Figure 7-12 shows the NO_2 concentration for the region and Figure 7-13 shows a close-up of NO_2 in the vicinity of the airport. The peak NO_2 for the Dallas region of 78 ppb occurs at the airport during this time. Figure 7-13 shows the difference in NO_2 with and without the use of reverse thrust. Table 7-11 shows the numerical NO_2 levels near the airport and the difference in concentrations resulting from the use of reverse thrust. With reverse thrust, NO_2 levels are increased by as much 14 ppb at the airport.

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

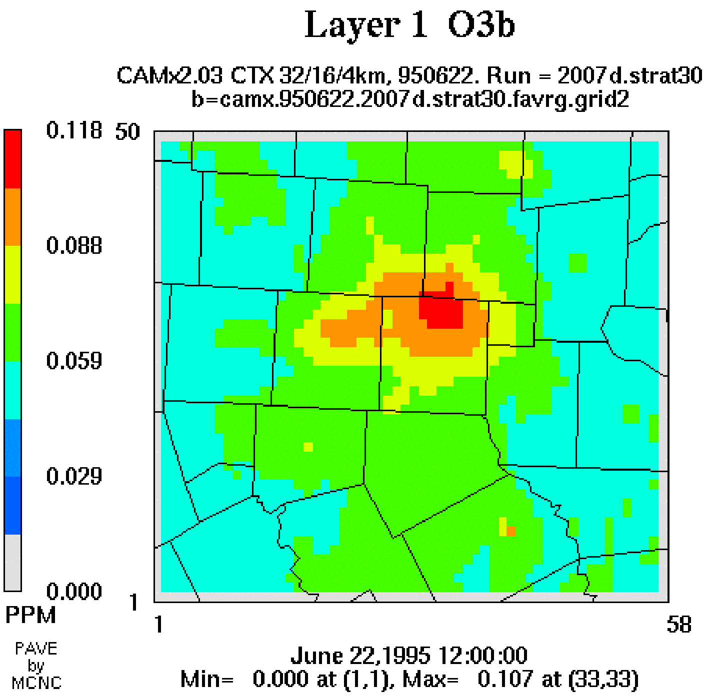


Figure 7-5 RT2 June 22, 12:00

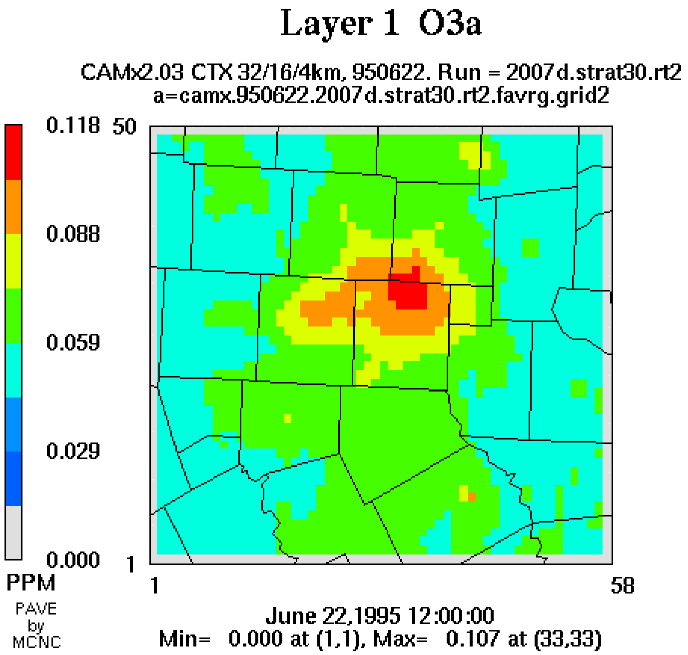


Figure 7-6 Base Case June 22, 16:00

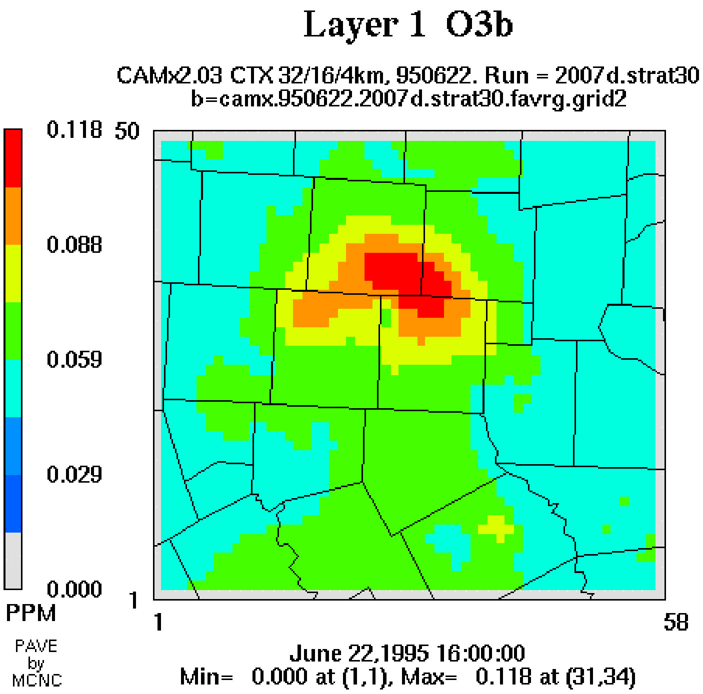


Figure 7-7 RT2, June 22, 16:00

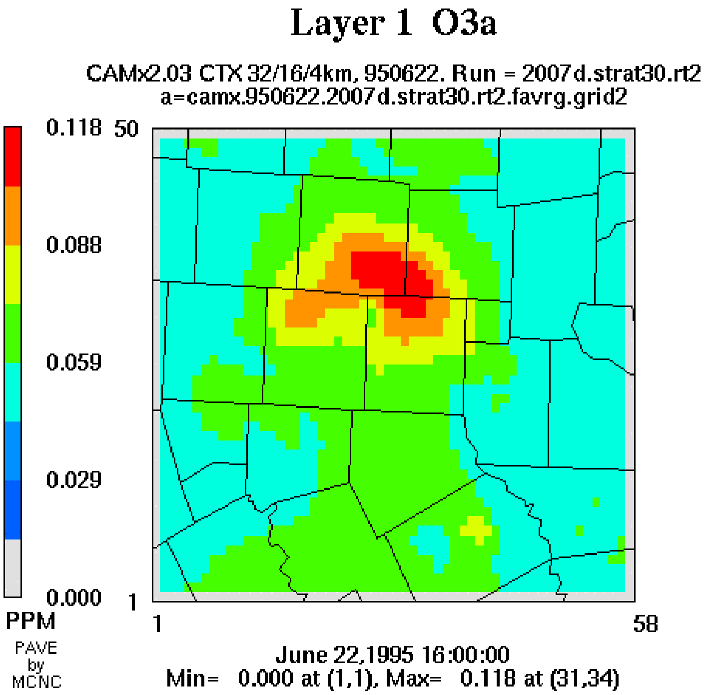


Figure 7-8 Base Case June 22, 19:00

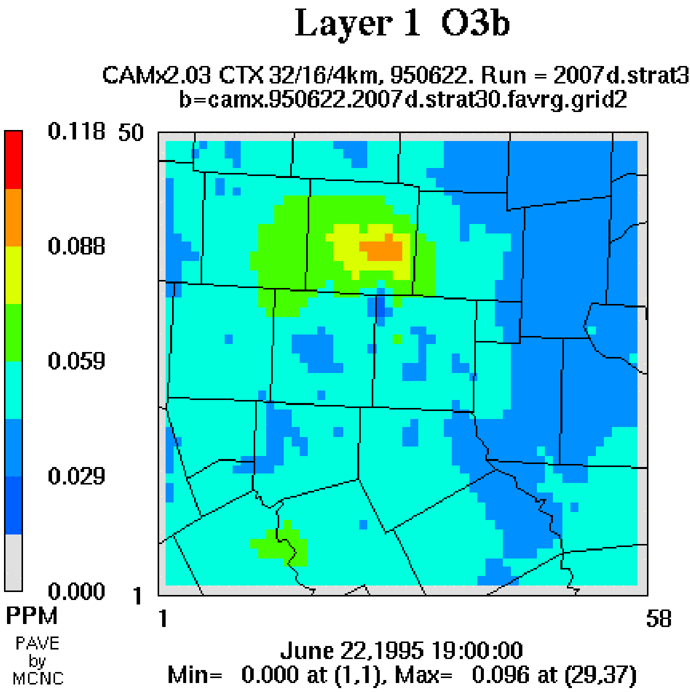


Figure 7-9 RT2, June 22 19:00

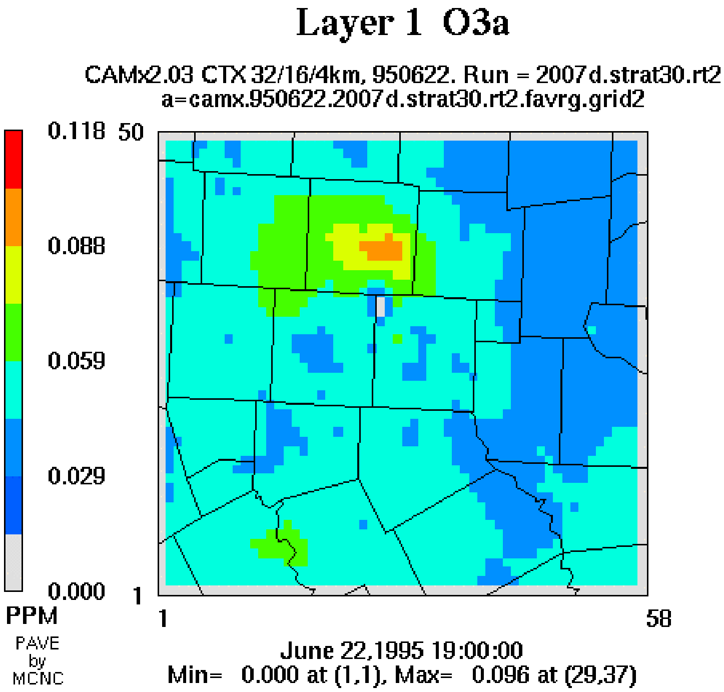


Figure 7-10 RT2 June 22, 19:00, Close-up

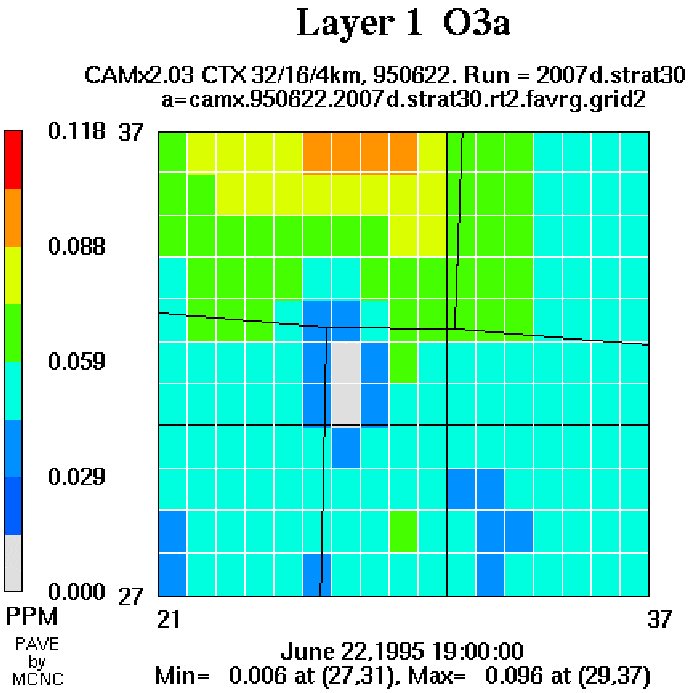


Table 7-8 RT2 Estimated Ozone Levels Near DFW at 19:00

Grid Cell		O_3 (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

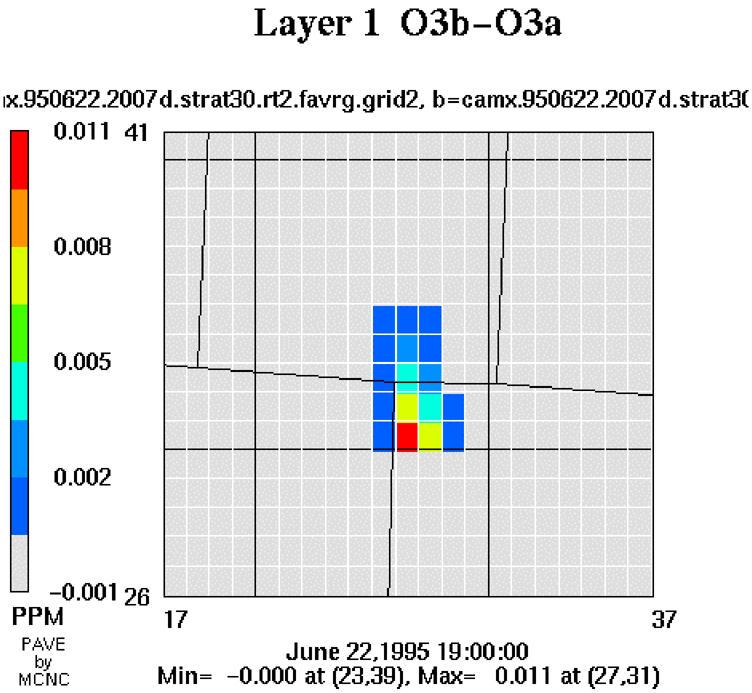


Table 7-9 Difference in O_3 resulting from reverse thrust

Grid Cell		$O_{3(RT)}$-$O_{3(base)}$ (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

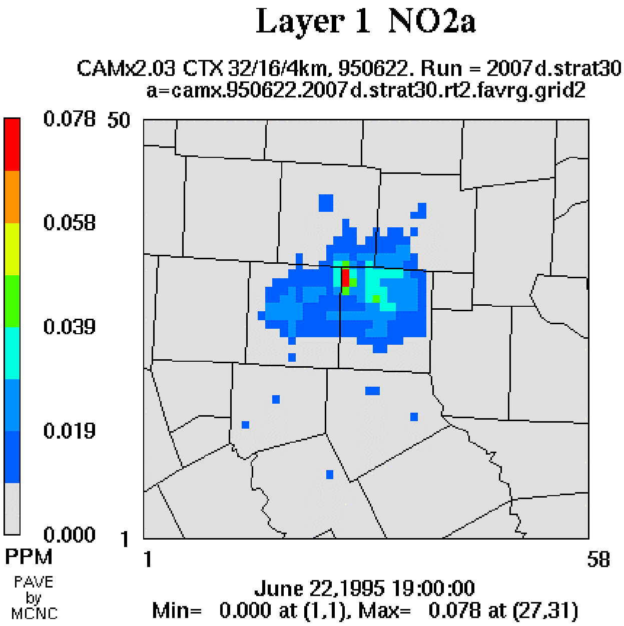


Figure 7-13 RT2, Nitrogen Dioxide, Close-Up

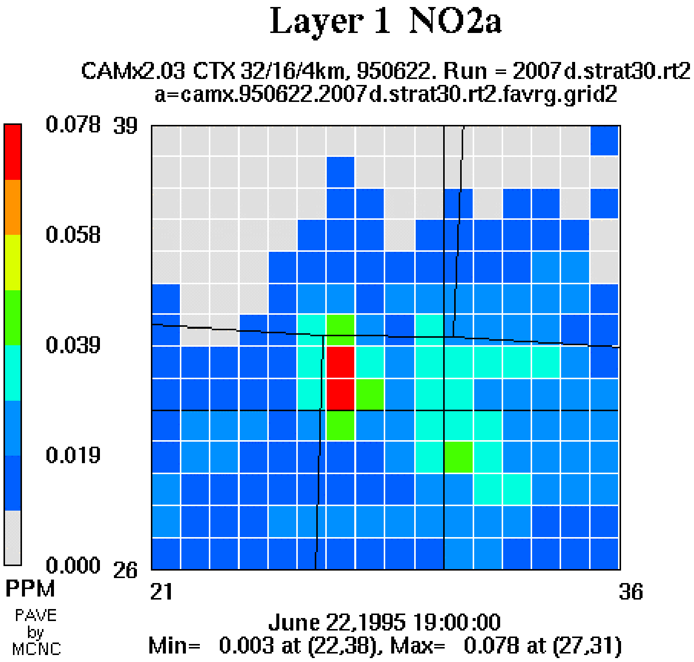


Figure 7-14 NO_2 Difference

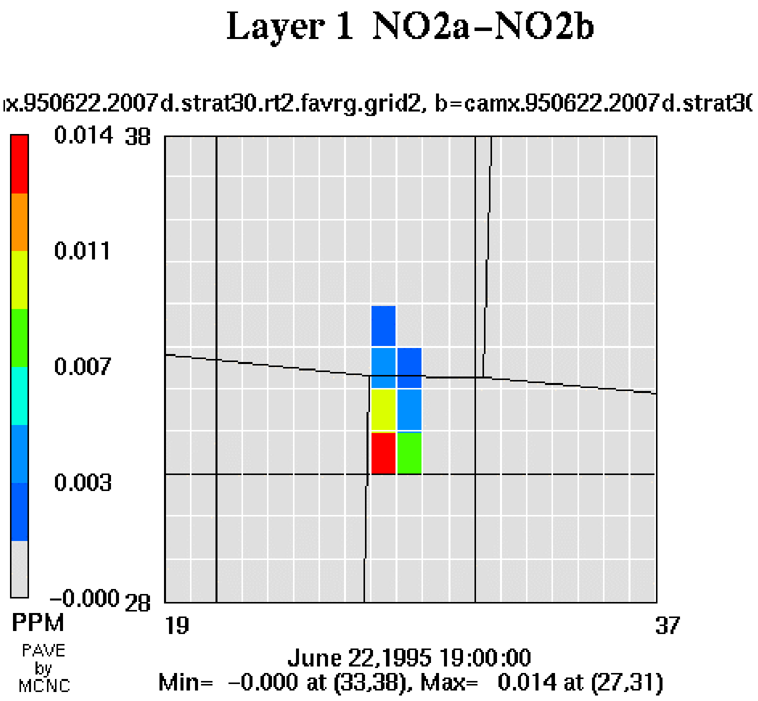


Table 7-10 NO_2 Levels Near DFW Airport

Grid Cell		$NO_{2(RT)}$ (ppb)	$NO_{2(RT)}$-$NO_{2(base)}$ (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

7.5 Discussion of NOx Scavenging

As discussed in Section 7.1, under normal conditions, nitric oxide quickly reacts with ozone to produce nitrogen dioxide and molecular oxygen. In the case of DFW Airport, this process is clearly evident in the evening, as the concentration of O_3 is sharply reduced and NO_2 is sharply increased. NO_2 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 NOx. Additional NOx emitted can increase ozone levels downwind from the airport. NOx itself is an irritant and there is an EPA standard for nitrogen dioxide. For NO_2, the NAAQS limit is an annual average of less than 55 ppb. High concentrations of NOx can result in discoloration and reduction in strength of fabrics. NO_2 is more toxic than NO and can also be the source of secondary air pollutants (Janssen, 1986). During the evening, NO_2 reacts with hydroxyl radicals to form nitric acid (HNO_3), which can cause corrosion of metal. High concentrations of NO_2 can also reduce crop yield and cause respiratory problems (Wark, Warner, and Davis, 1998). In Texas, the NO_2 standard has never been violated. For this model run, NO_2 levels were forecasted to be above 55 ppb for 3 hours of the day, because of the airport.

7.6 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_2 levels are elevated, as the result of NOx scavenging. Since emissions from reverse thrust are not currently considered, the on-airport contribution of NOx is underestimated by nearly 15%. Because of the resulting increase in NO_2 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_2 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_2 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.

8.0 FEASIBILITY

This chapter looks at the legal and operational ramifications for restricting the use of reverse thrust. The first section probes into the recent electric GSE proposal for Dallas/Ft. Worth. It provides an overview of the federal regulations pertaining to air transportation and air quality. It also discusses the EPA and FAA’s interpretation of these regulations and previous attempts to implement restrictions on aircraft for air quality purposes. The following sections evaluate the operational implications of a reverse thrust restriction. 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 NOx standard is proposed by the author, which would require a “phaseout” of high NOx emitting aircraft engines.

8.1 DFW Electric GSE Proposal: Policy Analysis

Air transportation is the fastest growing mode of transportation. Nationwide, the number of air travelers is expected to double roughly every 20 years or sooner. Previously, emissions reduction strategies at airports have focused on ground service equipment and passenger vehicles. Initially, TNRCC demanded 100% electrification of GSE at Dallas area airports by 2005 (TNRCC, 1999). This was forecasted to reduce NOx from GSE by 90%. On the landside, a 50% reduction in NOx will result from fleet turnover as new passenger vehicles become cleaner. However, as NOx emissions from GSE and passenger vehicles decrease, NOx emissions from aircraft will continue to increase with traffic growth and may offset the reductions achieved, as discussed in Section 2.6.

Based on the results of the air quality modeling, reverse thrust is shown to have a localized impact on air quality at Dallas/Ft. Worth International Airport. At other busy airports, emissions from reverse thrust are estimated to have similar effects. The air quality in the vicinity of the airport is most affected by the use of reverse thrust. As discussed in Chapter 7, airport employees and nearby residents are exposed to elevated levels of NO_2. The increased levels of NO_2 would have the greatest effect on the airline ground crews, who spend the majority of their work day outside.

As discussed in Chapter 2, TNRCC previously passed a proposal which would require 100% electrification of ground service equipment by 2005, to reduce NOx emissions. This proposal was being challenged in court with the Air Transport Association (ATA) representing the airlines. ATA contended that the GSE emissions at DFW were overestimated.

As shown in Section 2.6, GSE NOx emissions at DFW were projected to exceed the NOx produced by aircraft. URS Greiner, who developed DFW’s 1998 Emissions Inventory, assumed that the airport’s ratio of GSE emissions to LTO cycles would be similar to the ratio at El Paso (ELP) and Houston Intercontinental Airports (IAH). As a connecting hub, DFW’s function is much different than El Paso’s. The terminal layout of DFW is much different than IAH’s and the traffic level at DFW is twice as high.

The ATA argued that the FAA bars regulation of aircraft operations. TNRCC argues that although it may lack jurisdiction over aircraft, it does have the right to regulate ground activity at airports. The basis for all parties' arguments are in the U.S. Code of Federal Regulations. Deregulation of air travel is discussed in 49 USC § 41713. Paragraph B states:

> (1) Except as provided in this subsection, a State, political subdivision of a State, or political authority of at least 2 States may not enact or enforce a law, regulation, or other provision having the force and effect of law related to a price, route, or service of an air carrier that may provide air transportation under this subpart.

This clause is commonly known as preemption and it effectively bans state regulation of aircraft operations. State law cannot supersede federal law. Any pollution control measure which specifically targets aircraft would violate the law. This clause has also been upheld in many court cases involving airlines and municipalities (Dykeman, 2000).

As a result, a mandatory restriction on the use of reverse thrust would not be possible and all pollution reduction measures involving aircraft must be voluntary. However, according to the Clean Air Act, states and local governments are responsible for implementation of pollution control measures. Title 42 USC § 7401, paragraph A states:

> (3) that air pollution prevention (that is, the reduction or elimination, through any measures, of the amount of pollutants produced or created at the source) and air pollution control at its source is the primary responsibility of States and local governments

States are given the authority to regulate on-road and other non-road mobile sources. In 42 USC § 7543, states are given the power to enforce the federal emissions standards for motor vehicles. However, states must use standards which are equally stringent with the federal standards. Airport GSE, which are mostly considered non-road mobile sources are largely unregulated. To develop emissions standards for non-road vehicles, the EPA Administrator will authorize the state of California to create them as necessary. This is discussed in 42 USC § 7543, paragraph 2. No emissions standards currently exist for airport GSE, although standards may be implemented in the future.

> (A) In the case of any nonroad vehicles or engines other than those referred to in subparagraph (A) or (B) of paragraph (1), the Administrator shall, after notice and opportunity for public hearing, authorize California to adopt and enforce standards and other requirements relating to the control of emissions from such vehicles or engines if California determines that California standards will be, in the aggregate, at least as protective of public health and welfare as applicable Federal standards.

The EPA and the FAA disagreed on whether preemption applies to airport GSE. Congress recently emphasized by using the Airport Noise and Capacity Act, 49 USC § 47521, that the federal government is against “uncoordinated and inconsistent restrictions on aviation that could impede the national air transportation system”. Requiring all-electric GSE in Dallas only could have created an unnecessary burden for the airlines by forcing them to replace their fleet. Suppliers could take advantage of the unbalanced demand for electric GSE and unfairly inflate prices.

A letter dated June 23, 2000 from EPA Region 6 Administrator Gregg Cooke to Robert Huston, Chairman of TNRCC, is included in the Appendix. In the letter, the EPA concluded that the "Texas regulation is not preempted by the Clean Air Act", as it only prohibits states from developing emissions standards for non-road vehicles. The EPA believes that the GSE regulation itself does not create an emissions standard "as long as there are…[other] alternatives for compliance."

"If a regulated party has valid alternatives for compliance that are not emissions standards, then the state is requiring a choice among alternatives and is not enforcing an emissions standard." (Cooke, 2000).

A letter from Paul Dykeman, Deputy Director of the FAA Office of Environment and Energy, to Donald Zinger, Assistant Director for the EPA Office of Transportation and Air Quality is also included in the Appendix. In this letter, the FAA stated that the major issue is whether the TNRCC regulation allows airlines to choose among suggested emissions reduction measures and the freedom to choose measures which do not impact aircraft operations. The FAA was unable to determine whether or not compliance with the TNRCC regulation will affect growth in aircraft operations.

The FAA also states that the "availability of reliable GSE is accordingly essential to safe and efficient use of the navigable airspace." It was also suggested that compliance cannot be achieved without reducing total GSE, which would have reduced aircraft flights. The FAA also has concerns about the facilities required for electric GSE, battery life and charging times.

"The electrification alternative potentially reduces the availability of GSE during peak periods of airport operation," stated the FAA. "Limitations on the total numbers of GSE available at any time would create difficulties in scheduling flights and increase congestion and delays." Questions also arose concerning the feasibility of the regulation, including electric grid requirements and whether or not the electric GSE will be affordable. The FAA believed that TNRCC has not fully considered all of the implications (Dykeman, 2000).

A settlement was reached in the ATA lawsuit during summer 2001. The airlines agreed to a voluntary 75% reduction in GSE emissions by 2005. The settlement also presented revised estimates of GSE NOx emissions for the Dallas region. A total of 6.8 tons per day of NOx are emitted by GSE in the region. Approximately 85% of this total or 5.8 tons of NOx per day is produced by DFW Airport. At DFW Airport, American produces 75% or 4.4 tons per day of the GSE emissions, Delta produces 20% or 1.16 tons per day, and the remaining airlines produce 5% or 0.2 tons per day (TNRCC Agreed, 2001). Since the airline GSE emissions reductions are not mandated, it is unlikely that these levels of reduction will actually be achieved.

Over the years, several trade organizations have lobbied for amendments or repeals of environmental regulations. In September 1974, ATA filed a petition requesting an extension of the compliance date for reducing smoke emissions from JT3D engines, used on B707 and DC-8 aircraft. When the first aircraft emissions standards were implemented in 1973, limits on smoke emissions were placed on all aircraft engines. Most JT8D engines were retrofitted with low smoke combustor kits by the end of 1974. However, due to developmental problems, new combustor kits for JT3D engines were not available until 1978. A proposal to extend the deadline for compliance until 1981 was adopted in December 1976. The new deadline was formally adopted by the EPA in 1979.

Later, the JT3 engine retrofit program was suspended by the EPA after the AVMARK Corporation, an aviation management service firm, filed a petition. Many airlines were opting to sell or retire their B707s and DC-8 instead of retrofitting them. (EPA, 1979). Companies buying these surplus airplanes were small operators developed after deregulation, who were often unfamiliar with the retrofit requirement. The petition argued that the "steady migration of JT3D powered aircraft from first-line service to more intermittent usage with small new operators has greatly reduced their environmental impact." (EPA,1979).

An all-out ban on reverse thrust during landing would be nearly impossible to implement in the United States. Furthermore, it would not be desirable restrict reverse thrust during inclement weather or at airports with short runways. A voluntary restriction during landing. should be considered during days with the potential for elevated levels of ozone. Also, many U.S. airports have prohibited the power-backing of aircraft, which is usually justifiable for safety reasons. Prohibition of power-backing is discussed in the following section.

8.2 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.

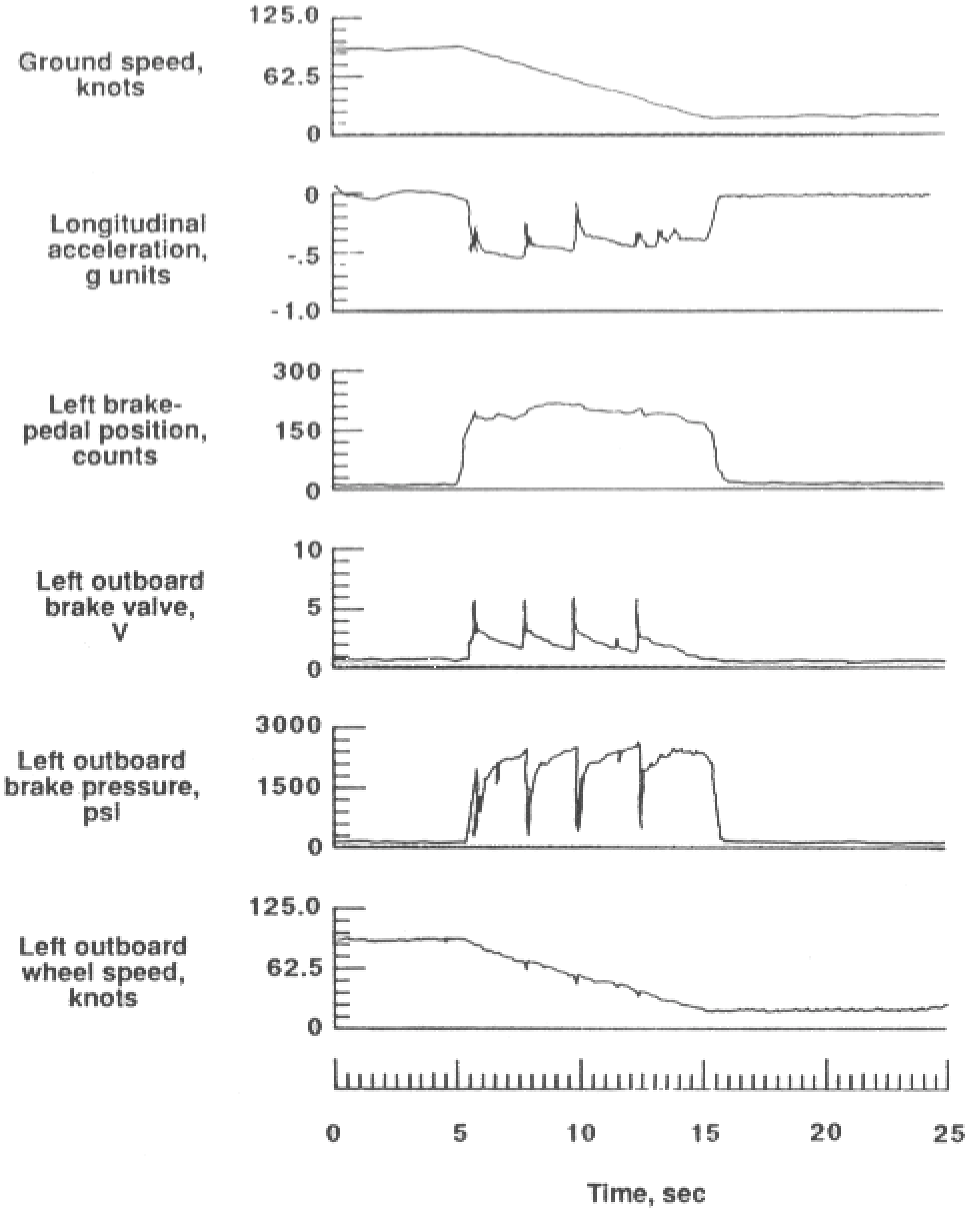
8.3 Feasibility

8.3.1 Wheel Braking

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.

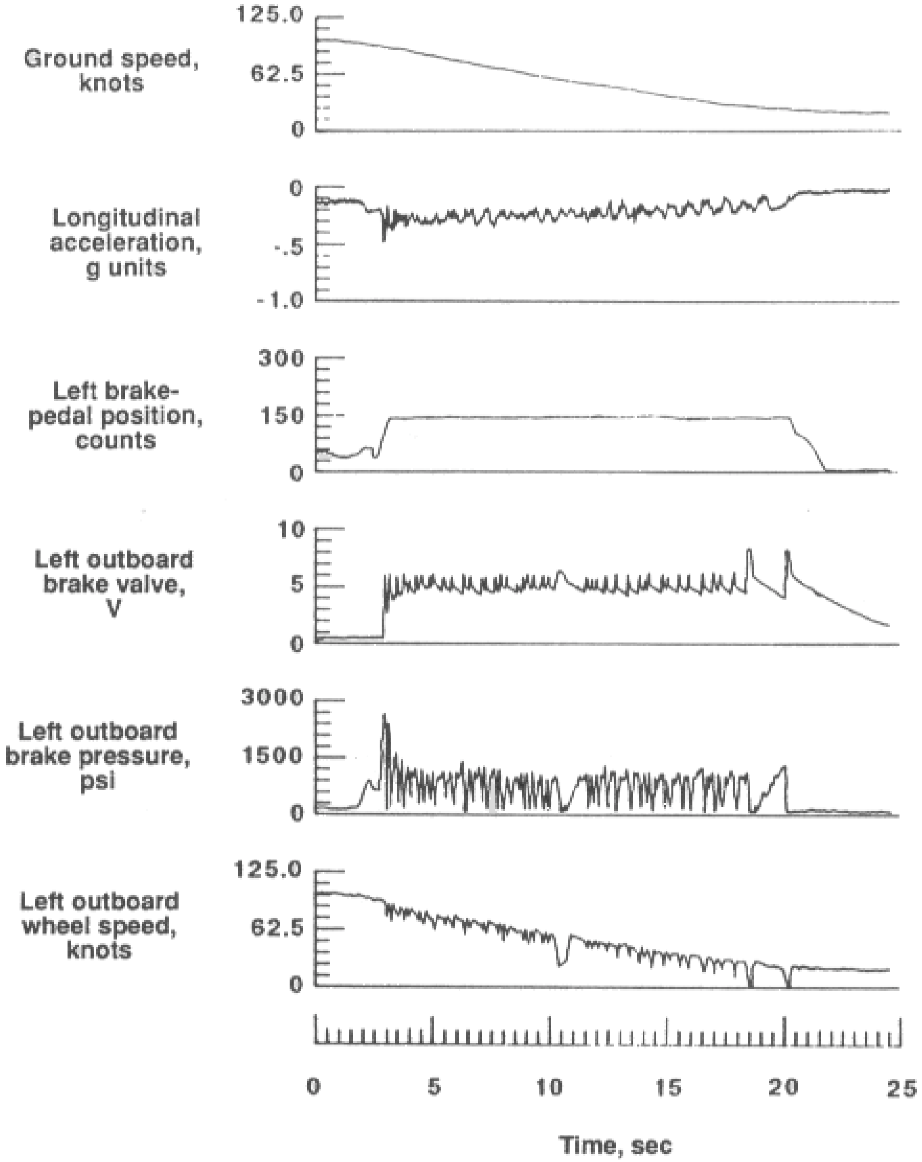
In Yager, Vogler, and Baldasare (1990), braking tests were conducted on Boeing 727 and B737 aircraft. Tests were conducted under a multitude of runway conditions, including dry, wet, icy, and snow-covered. When maximum anti-skid braking was applied on a dry runway for the B727, the aircraft decelerated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

8.3.2 European Experience

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

8.3.3 Impact on Airport Operations

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.

8.4 Other Considerations

8.4.1 Overestimation of Emissions

Several sources have suggested that the current aircraft emissions methodology may overestimate aircraft NOx 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 NOx 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 NOx. This more realistic and would make the emissions produced from reverse thrust even more significant. (Yamartino and Spitzak, 1994).

8.4.2 Proposed NOx Standard Revision

Currently, all aircraft engines are able to meet the ICAO NOx 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 NOx emissions reduction for aircraft would be strengthening the standard an additional 20% to the following:

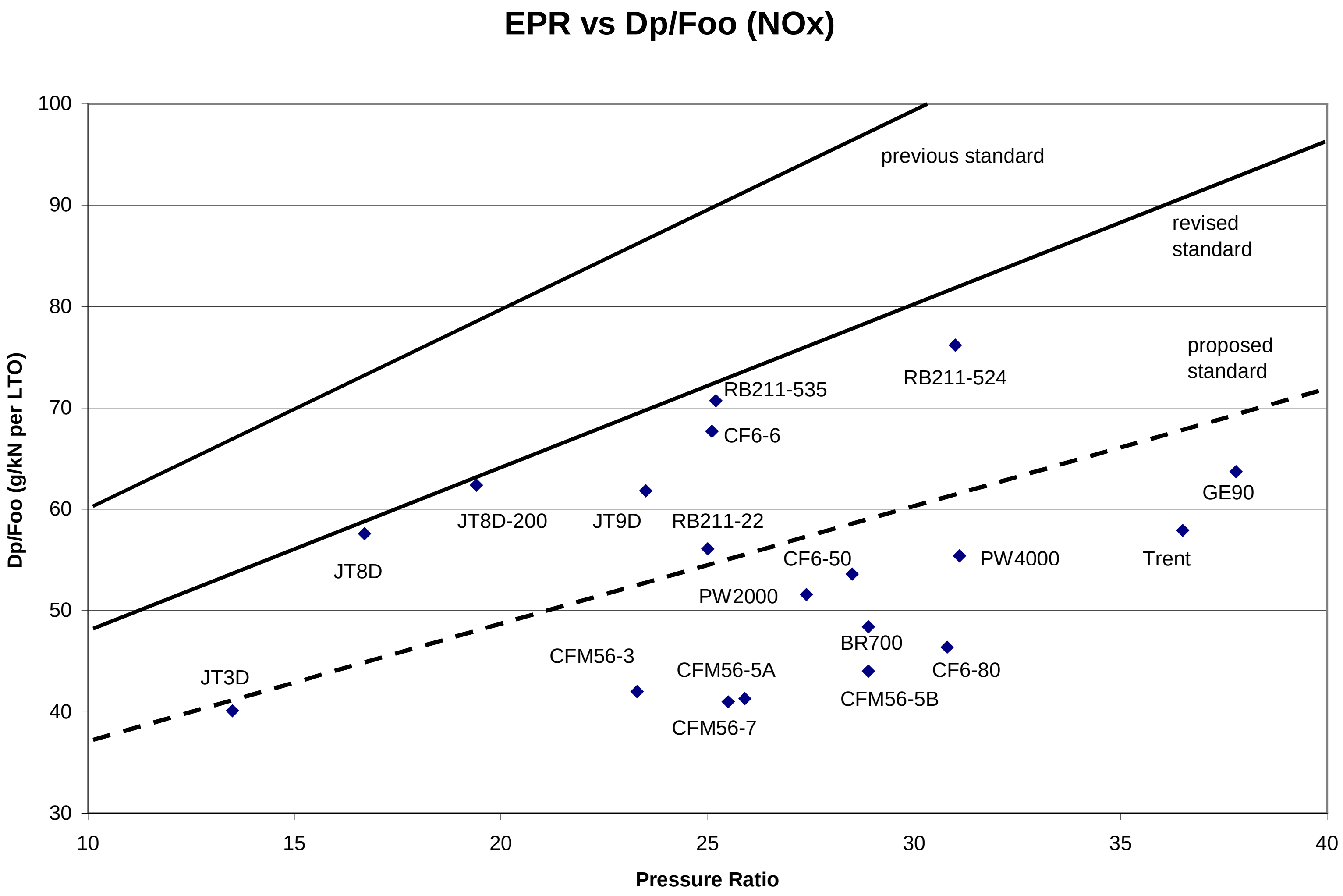
$$D_p/F_{00} = 24 + 1.2\pi_{00} \qquad (8\text{-}1)$$

where:

D_p = total mass of pollutant emitted during LTO
F_{00} = max thrust per engine
π_{00} = engine pressure ratio

Figure 8-2 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 NOx by 10-15%.

Figure 8-2 Proposed NOx standard



8.5 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. In the case of the Dallas GSE proposal, both parties provided valid arguments. Both parties' opinions also had a legal basis. 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.

9.0 CONCLUDING REMARKS

This chapter presents the conclusions and recommendations from this dissertation. Section 9.1 presents the overall conclusions and Section 9.2 presents the author's views on the significance of this research. Section 9.3 provides directions for future research.

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 NOx 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 NOx emissions by 15%. Because emissions from reverse thrust are a small fraction of regional NOx 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 NOx 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 NOx 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 NOx scavenging occurs, ozone reacts with NO to form NO_2. Elevated levels of NO_2 were found to occur near the airport. The peak NO_2 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_2 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_2 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_2 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 NOx 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 NOx, 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 Section 2.6, 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 NOx. As discussed in Section 8.1, a 75% reduction in GSE NOx 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 NOx 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 NOx associated with aviation-related activities will be produced by aircraft engines. No major NOx 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 NOx.

Beyond the year 2007, the proportion of regional NOx 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 NOx 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 NOx from increasing, a stricter NOx standard, similar to the one proposed by the author, is needed. As discussed in Section 8.3, revising the current ICAO NOx standard an additional 20% is shown in Equation 9-1.

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

where:

D_p = total mass of pollutant emitted during LTO
F_{00} = max thrust per engine
π_{00} = engine pressure ratio

9.3 Future Research

9.3.1 Validation of TIMs and Power Settings

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.

9.3.2 Noise from Reverse Thrust

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.

9.3.3 Additonal Air Quality Simulation

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 NOx over a small area. However, as discussed by Chapter 8, the estimated NOx emissions associated with GSE at DFW are thought to have been overestimated. The current GSE contribution of NOx 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 NOx from GSE would occur. With the recent settlement between the ATA and TNRCC, the airport's contribution of regional NOx may be much larger. Depending on the amount of voluntary NOx 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.

APPENDIX

Landing NOx Emissions Estimate for DFW

aircraft	engine	LTOs	# engines	EI(NOx) 85% (g/kg)	EI(NOx) 30% (g/kg)	fuel flow (kg/s)	t-r time (sec)	Total NOx @85% (g)	Total NOx @80% (g)
A300-B4-200	CF6-50C2	537	2	29	10.16	1.915	15.4	978171.276	866097.26
A310-200	CF6-80A	537	2	26.6	10.3	1.885	15.4	883163.5176	784760.81
A320-200	CFM56-5-A1	948	2	19.6	8	0.862	15.4	525346.1069	467752.97
A340-300	CFM56-5C2	537	4	25.8	10	1.076	15.4	977935.2538	869004.71
B727-200	JT8D-15	40058	3	15	5.9	0.945	15.4	31343782.68	27867833
B737-200	JT8D-15	11570	2	15	5.9	0.945	15.4	5280952.95	4695308.1
B737-300	CFM56-3-B1	5878	2	16.7	8.366667	0.878	15.4	2947587.288	2647854.9
B737-400	CFM56-3C-1	2444	2	17.8	9.1	0.954	15.4	1419370.206	1276281.3
B747-200	JT9D-7A	294	4	25.6	0	1.9996	15.4	987266.1873	844561.35
B757-200	PW2040	22118	2	27.3	10.6	1.448	15.4	28678135.1	25485398
B757-200	RB211-535E4	9947	2	36.2	7.5	1.51	15.4	15006752.43	13103567
B767-200	CF6-80C2A1	4367	2	26.6	9.76	1.885	15.4	7182076.502	6369371.8
B767-300	CF6-80C2A5	4367	2	22.94	11.6	2.081	15.4	6837896.602	6145300.1
DC 10-30	CF6-50C2	4223	3	25.5	10.16	1.94	15.4	10278461.05	9143087.2
DC8-51	JT3D-3B	1732	4	9.9	4.8	0.932	15.4	1048341.635	940290.25
DC8-70	CFM56-3-B1	2043	4	16	8.366667	0.819	15.4	1756208.563	1580917.3
DC9-10	JT8D-7	15860	2	14	5.5	0.8113	15.4	5043949.456	4484382.2
FOKKER 100	TAY Mk620-15	35799	2	12.94	5.7	0.71	15.4	9932771.925	8871324.7
L-1011-150	RB211-22B	815	3	25.63	8.05	1.542	15.4	1584731.503	1398245.2
L-1011-200	RB211-22B	815	3	25.63	8.05	1.542	15.4	1584731.503	1398245.2
MD-11	CF6-80C2D1F	2103	3	24.02	9.16	2.065	15.4	5132127.468	4557725.4
MD-80-82	JT8D-219	149985	2	20.8	9.13	1.085	15.4	97484010.62	87053618
MD-90-10	V2525-D5	7589	2	22.3	8.9	0.88	15.4	4884790.381	4345490
Total (tons/yr)									**224.6**

Landing NOx Emissions Estimate for IAH

aircraft	engine	LTOs	# of engines	EI(NOx) @85% (g/kg)	EI(NOx) @30% (g/kg)	fuel flow (kg/s)	time	NOx@ (85%) (g)	NOx @80% (g)
F-100	TAY 650	4,680	2	12.94	5.26	0.71	16	1,375,905	1,224,869.24
737-500	CFM56-3B-2	17,863	2	16.7	8.7	0.878	16	8,381,377	7,543,407.90
737-400	CFM56-3C-1	416	2	17.8	9.1	0.954	16	226,054	203,264.91
737-300	CFM56-3B-2	30,706	2	16.7	8.7	0.878	16	14,407,353	12,966,908.30
737-200	JT8D-15	8,587	2	15	5.9	0.945	16	3,895,063	3,463,110.13
757-200	RB211-535E4	2,561	2	36.2	7.5	1.448	16	4,295,727	3,750,934.67
767-200	CF680C2	3	2	24.9	9.76	1.885	16	4,506	4,005.68
767-300	CF6-80C2A5	7	2	22.86	11.6	2.082	16	10,661	9,582.94
DC-9-15	JT8D-7	12	2	14	5.5	0.8113	16	4,362	3,877.69
DC-9-30	JT8D-11	21,962	2	14.6	5.8	0.9136	16	9,374,127	8,337,707.71
MD-80	JT8D-219	31,667	2	20.8	9.13	1.085	16	22,869,147	20,422,241.58
MD-90	V2525-D5	7	2	22.3	8.9	0.88	16	4,396	3,910.46
A300-B4	CF6-50C2	2	2	25.5	10.16	1.94	16	3,166	2,816.35
A300-600	CF6-80C2A5	151	2	22.86	11.6	2.082	16	229,977	206,717.67
A310-200	CF680A	209	2	25.6	10.3	1.885	16	322,736	287,194.24
A320	CFM56-5-A1	16	2	19.6	8	0.862	16	8,650	7,702.01
727-100	JT8D-7	1,592	3	14	5.5	0.8113	16	867,948	771,659.50
727-200	JT8D-15	16,588	3	15	5.9	0.945	16	11,286,475	10,034,832.46
DC-10-10	CF6-6D	103	3	32.6	11.4	1.431	16	230,641	204,202.06
DC-10-30	CF6-50C2	1,062	3	25.5	10.16	1.94	16	2,521,783	2,243,222.91
L-1011	RB211-22B	62	3	25.63	8.05	1.542	16	117,616	103,775.19
747-100	JT9D-7A	15	4	25.6	0	1.9996	16	49,142	42,038.89
747F	JT9D-7A	51	4	25.6	0	1.9996	16	167,083	142,932.23
DC-8-50	JT3D-3B	325	4	9.9	4.8	0.932	16	191,917	172,136.73
DC-8-70	CFM56-2-C5	35	4	16	8.2	0.819	16	29,353	26,397.02
								80.9	72.2

Landing NOx Emissions Estimate for HOU

4	engine	# engines	LTOs	EI(NOx) @85% (g/kg)	EI(NOx) @30% (g/kg)	fuel flow (kg/s)	time	NOx@ (85%) (g)	NOx @80% (g)
727-100	JT8D-7	3	8	14	5.5	0.8113	16	4361.5	3877.7
727-200	JT8D-15	3	218	15	5.9	0.945	16	148327.2	131878.1
737-200	JT8D-15	2	19,918	15	5.9	0.945	16	9034804.8	8032866.9
737-300	CFM56-3B-2	2	24,414	16.7	8.7	0.878	16	11455126.9	10309845.0
737-500	CFM56-3B-2	2	4,473	16.7	8.7	0.878	16	2098745.9	1888913.6
A320	CFM56-5-A1	2	36	19.6	8	0.862	16	19463.3	17329.5
DC-9-15	JT8D-7	2	72	14	5.5	0.8113	16	26169.3	23266.1
DC-9-30	JT8D-11	2	4,213	14.6	5.8	0.9136	16	1798251.3	1599433.7
DC-9-50	JT8D-15	2	515	15	5.5	0.945	16	233604.0	207165.0
MD-80	JT8D-219	2	1,294	20.8	9.13	1.085	16	934495.7	834508.5
Total (tons/yr)								**25.75**	**23.05**

Landing NOx Emissions Estimate for AUS

aircraft	engine	# engines	LTOs	EI(NOx) @85% (g/kg)	EI(NOx) @30% (g/kg)	fuel flow (kg/s)	time	NOx@ (85%) (g)	NOx @80% (g)
DC-8-50/60	JT3D-3B	4	273	9.9	4.8	0.932	16	161210.6	144594.9
F100	TAY 650	2	1608	12.94	5.26	0.71	16	472746.9	420852.5
727-100	JT8D-7	3	316	14	6.3	0.8113	16	172281.2	154010.8
DC-9-15	JT8D-7	2	12	14	6.3	0.8113	16	4361.549	3899.007
DC-9-10	JT8D-7	2	69	14	6.3	0.8113	16	25078.91	22419.29
DC-9-40	JT8D-11	2	125	14.6	5.8	0.9136	16	53354.24	47455.31
DC-9-30	JT8D-11	2	3141	14.6	5.8	0.9136	16	1340685	1192457
727-200	JT8D-15	3	2428	15	6.9	0.945	16	1652011	1478229
DC-9-50	JT8D-15	2	285	15	6.9	0.945	16	129276	115676.9
737-200	JT8D-15	2	6276	15	6.9	0.945	16	2846794	2547326
DC-8-70	CFM56-2-C5	4	79	16	8.2	0.819	16	66253.82	59581.84
737-300	CFM56-3B-2	2	10717	16.7	8.7	0.878	16	5028451	4525707
737-500	CFM56-3B-2	2	3005	16.7	8.7	0.878	16	1409956	1268988
737-400	CFM56-3C-1	2	23	17.8	9.1	0.954	16	12498.16	11238.2
A320	CFM56-5-A1	2	1	19.6	8	0.862	16	540.6464	481.3759
MD-80	JT8D-219	2	9284	20.8	9.1	1.085	16	6704682	5986481
MD-90	V2525-D5	2	497	22.3	8.9	0.88	16	312100.1	277643
737-300	CF6-80C2B6	2	3	22.94	9.11	2.081	16	4582.861	4076.119
MD-11	CF6-80C2D1F	3	2	24.02	9.16	2.065	16	4761.725	4228.779
DC-10-40	CF6-50C2	3	1	25.5	10.16	1.94	16	2374.56	2112.263
DC-10-10	CF6-6D	3	4	32.6	11.4	1.431	16	8956.915	7930.177
757-200	RB211-535E4	2	210	36.2	7.5	1.448	16	352246.3	307573.7
Total (tons/yr)								**20.8**	**18.6**

Summary of Data Collection by Day

date	datapoints	rwy	analyzer	hours
6-Nov	20	west	C	4
9-Nov	20	east	C	5
10-Nov	22	east	C	7.66
14-Nov	24	east	E	8
15-Nov	22	west	C	4.75
17-Nov	31	west	C	6
20-Nov	20	east	E	7
21-Nov	11	east	C	4
21-Nov	19	west	C	4
26-Nov	14	east	C	4
26-Nov	27	west	C	4.5
27-Nov	19	east	C	8
27-Nov	27	west	E/C	8
28-Nov	15	east	C	8
28-Nov	50	west	C	8
30-Nov	18	east	C	8
30-Nov	47	west	C	8
4-Dec	42	west	C	8
4-Dec	25	east	C	8
5-Dec	17	east	C	7.75
5-Dec	52	west	C	8
6-Dec	18	west	C	4
7-Dec	41	west	C	7.75
8-Dec	35	west	C	8
	636			158.41

Landing Data Observations

date	time	airline	aircraft	runway	duration
11/10/00	939	SW	733	17L	18.4
11/10/00	941	DL	M80	17L	14.3
11/10/00	944	CO	M80	17L	12.8
11/10/00	946	SW	733	17L	27.1
11/10/00	949	SW	733	17L	18.5
11/10/00	953	TW	M80	17L	16.6
11/10/00	1004	AA	M80	17L	15.5
11/10/00	1011	DL	M80	17L	7
11/10/00	1017	SW	733	17L	16.9
11/10/00	1037	NW	DC9	17L	12.9
11/10/00	1136	SW	733	17L	11.5
11/10/00	1138	TW	DC9	17L	12.1
11/10/00	1211	SW	733	17L	12.8
11/10/00	1347	SW	733	17L	16.5
11/10/00	1350	DL	737	17L	9.6
11/10/00	1413	UA	733	17L	20.5
11/10/00	1432	DL	72S	17L	15.7
11/10/00	1451	NW	DC9	17L	13.5
11/10/00	1503	CO	M80	17L	12.5
11/10/00	1517	SW	733	17L	16.1
11/10/00	1535	AA	M80	17L	11.8
11/10/00	1538	SW	733	17L	19
11/21/00	1006	SW	733	17L	19.1
11/21/00	1010	DL	M80	17L	10.9
11/21/00	1040	SW	733	17L	13.8
11/21/00	1059	NW	DC9	17L	10.1
11/21/00	1155	TW	DC9	17L	10.5
11/21/00	1222	SW	733	17L	15.5
11/21/00	1231	SW	737	17L	16.3
11/27/00	955	SW	733	17L	16.8
11/27/00	957	SW	733	17L	23
11/27/00	1024	NW	DC9	17L	17.6
11/27/00	1033	DL	M80	17L	9.2
11/27/00	1045	CO	M80	17L	15.6
11/27/00	1136	TW	DC9	17L	12.3
11/27/00	1156	AA	M80	17L	14.7
11/27/00	1204	biz	jet	17L	
11/27/00	1208	SW	733	17L	23.4
11/27/00	1322	SW	733	17L	13.1
11/27/00	1327	DL	72S	17L	12.8
11/27/00	1350	SW	733	17L	15
11/27/00	1429	DL	737	17L	17.1
11/27/00	1453	NW	DC9	17L	12.5
11/27/00	1508	DL	72S	17L	26.3
11/27/00	1511	CO	M80	17L	13.6
11/27/00	1538	SW	737	17L	22.2
11/27/00	1614	CO	M80	17L	10.9
11/27/00	1624	SW	737	17L	20.9
11/27/00	1647	SW	737	17L	9.2
11/28/00	1038	NW	DC9	17L	13.3
11/28/00	1125	AA	M80	17L	16.3
11/28/00	1134	SW	733	17L	20.4
11/28/00	1140	TW	DC9	17L	10.4
11/28/00	1212	SW	733	17L	14.6
11/28/00	1307	DL	72S	17L	15.1

11/28/00	1358	DL	737	17L	17
11/28/00	1503	DL	72S	17L	12.2
11/28/00	1540	SW	733	17L	20
11/28/00	1617	DL	737	17L	14
11/28/00	1650	DL	72S	17L	27.4
11/28/00	1704	SW	737	17L	13.2
11/28/00	1711	SW	733	17L	16.8
11/28/00	1734	NW	DC9	17L	15
11/28/00	1736	SW	733	17L	17.4
11/30/00	1050	AA	M80	17L	12.2
11/30/00	1128	NW	DC9	17L	9
11/30/00	1131	TW	DC9	17L	17.3
11/30/00	1135	SW	733	17L	11.9
11/30/00	1142	AA	M80	17L	14.6
11/30/00	1208	AA	M80	17L	8.3
11/30/00	1255	DL	72S	17L	15.8
11/30/00	1309	SW	733	17L	15.8
11/30/00	1338	SW	733	17L	22.4
11/30/00	1431	DL	72S	17L	11.4
11/30/00	1451	NW	DC9	17L	14.4
11/30/00	1510	SW	733	17L	16.3
11/30/00	1527	SW	733	17L	16
11/30/00	1543	SW	737	17L	15.9
11/30/00	1652	AA	757	17L	11.9
11/30/00	1705	unknown	733	17L	21.6
11/30/00	1720	TW	DC9	17L	17
11/30/00	1754	SW	737	17L	24.6
12/4/00	911	TW	M80	17L	14.1
12/4/00	939	SW	733	17L	15.4
12/4/00	944	DL	M80	17L	8.1
12/4/00	1006	DL	M80	17L	idle rev
12/4/00	1024	NW	DC9	17L	10.9
12/4/00	1130	TW	DC9	17L	17.1
12/4/00	1135	SW	733	17L	17.2
12/4/00	1208	AirForce	T38	17L	
12/4/00	1211	SW	733	17L	17.2
12/4/00	1216	AA	M80	17L	11.3
12/4/00	1234	DL	M80	17L	8.8
12/4/00	1300	biz	jet	17L	20.3
12/4/00	1343	SW	733	17L	16.1
12/4/00	1346	DL	737	17L	13.8
12/4/00	1359	AA	M80	17L	11.3
12/4/00	1442	NW	DC9	17L	10.9
12/4/00	1445	DL	72S	17L	13.4
12/4/00	1523	AA	M80	17L	14.1
12/4/00	1619	DL	737	17L	15
12/4/00	1626	SW	737	17L	19.8
12/4/00	1643	AA	757	17L	15.2
12/4/00	1644	DL	72S	17L	10.4
12/4/00	1646	AA	M80	17L	9.8
12/4/00	1649	SW	737	17L	15.1
12/4/00	1655	AA	757	17L	14.4
12/4/00	1707	SW	733	17L	13.6
12/5/00	1037	NW	DC9	17L	18.3
12/5/00	1049	AA	M80	17L	13.6
12/5/00	1133	TW	DC9	17L	11.6
12/5/00	1146	SW	733	17L	18.9
12/5/00	1205	SW	733	17L	12.6
12/5/00	1250	DL	M80	17L	17.6

12/5/00	1353	SW	733	17L	19.4
12/5/00	1444	DL	72S	17L	13.3
12/5/00	1453	NW	DC9	17L	10.8
12/5/00	1511	AA	M80	17L	11.4
12/5/00	1626	SW	737	17L	21.9
12/5/00	1636	DL	737	17L	14.3
12/5/00	1639	DL	72S	17L	11
12/5/00	1653	SW	733	17L	13.8
12/5/00	1713	SW	733	17L	19.4
12/5/00	1724	TW	DC9	17L	13.7
12/5/00	1801	NW	DC0	17L	11.6
11/15/00	907	AA	M80	17R	22.3
11/15/00	928	SW	733	17R	16.8
11/15/00	933	CO	733	17R	24.2
11/15/00	945	SW	733	17R	17.7
11/15/00	956	CO	M80	17R	inaud
11/15/00	1002	AA	M80	17R	14.3
11/15/00	1010	SW	733	17R	14.7
11/15/00	1017	CO	M80	17R	13.7
11/15/00	1123	SW	733	17R	16.5
11/15/00	1128	CO	M80	17R	9.6
11/15/00	1137	AA	M80	17R	14.5
11/15/00	1141	AA	M80	17R	20.7
11/15/00	1143	TW	DC9	17R	13.1
11/15/00	1152	UA	733	17R	inaud
11/15/00	1204	AA	757	17R	13
11/15/00	1209	SW	733	17R	19.5
11/15/00	1217	SW	733	17R	18.4
11/15/00	1250	AA	M80	17R	13.1
11/15/00	1303	SW	733	17R	16.1
11/15/00	1317	CO	733	17R	15.4
11/15/00	1324	SW	733	17R	19.8
11/15/00	1329	AA	M80	17R	16.1
11/15/00	1335	SW	733	17R	16.7
11/15/00	1337	HP	733	17R	20.7
11/21/00	906	TW	M80	17R	8.3
11/21/00	927	SW	733	17R	11.4
11/21/00	931	CO	733	17R	11.8
11/21/00	942	SW	733	17R	18.9
11/21/00	955	AA	M80	17R	10.3
11/21/00	1003	Emery	DC8	17R	18.5
11/21/00	1006	CO	M80	17R	11.9
11/21/00	1011	SW	733	17R	13.4
11/21/00	1015	DL	M80	17R	17.8
11/21/00	1044	AA	M80	17R	15.9
11/21/00	1118	SW	733	17R	19.8
11/21/00	1131	AA	M80	17R	16.3
11/21/00	1135	AA	M80	17R	13.6
11/21/00	1139	CO	733	17R	16.1
11/21/00	1150	SW	737	17R	16.4
11/21/00	1156	AA	M80	17R	17.9
11/21/00	1159	UA	733	17R	19.7
11/27/00	905	AA	M80	17R	17.5
11/27/00	1009	AA	M80	17R	11
11/27/00	1015	CO	M80	17R	10.3
11/27/00	1017	SW	733	17R	20.4
11/27/00	1049	AA	M80	17R	20.1
11/27/00	1125	SW	733	17R	24.1
11/27/00	1133	AA	M80	17R	15.5

11/27/00	1148	AA	M80	17R	15.1
11/27/00	1204	SW	733	17R	16.9
11/27/00	1218	AA	M80	17R	10.9
11/27/00	1254	CO	M80	17R	17.5
11/27/00	1317	SW	733	17R	16.2
11/27/00	1320	UA	72S	17R	24.3
11/27/00	1324	AA	M80	17R	14.5
11/27/00	1329	HP	733	17R	19.3
11/27/00	1405	UA	733	17R	14.3
11/27/00	1407	AA	M80	17R	10.4
11/27/00	1432	AA	M80	17R	16.8
11/27/00	1449	DL	733	17R	21.8
11/27/00	1508	SW	733	17R	18.8
11/27/00	1510	AA	M80	17R	14.2
11/27/00	1530	SW	733	17R	14
11/27/00	1616	UA	733	17R	17.4
11/27/00	1630	unknown	733	17R	15.3
11/27/00	1634	HP	733	17R	22.3
11/27/00	1649	SW	733	17R	13
11/27/00	1654	AA	757	17R	15.1
11/28/00	1008	CO	M80	17R	23.5
11/28/00	1034	DL	M90	17R	20.7
11/28/00	1042	AA	M80	17R	19
11/28/00	1127	AA	M80	17R	14
11/28/00	1129	SW	733	17R	inaud
11/28/00	1132	CO	M80	17R	9.7
11/28/00	1135	AA	M80	17R	13.6
11/28/00	1144	UA	733	17R	20
11/28/00	1155	SW	737	17R	19.2
11/28/00	1159	SW	733	17R	8.2
11/28/00	1206	AA	M80	17R	15.3
11/28/00	1226	cargo	72S	17R	18.4
11/28/00	1229	AA	757	17R	inaud
11/28/00	1249	AA	M80	17R	13.3
11/28/00	1256	CO	M80	17R	14.7
11/28/00	1313	SW	733	17R	18.7
11/28/00	1325	AA	M80	17R	20.5
11/28/00	1335	UA	72S	17R	20.8
11/28/00	1340	SW	733	17R	21.2
11/28/00	1343	HP	733	17R	17.6
11/28/00	1349	SW	733	17R	16.1
11/28/00	1351	CO	733	17R	inaud
11/28/00	1402	SW	733	17R	15.2
11/28/00	1413	UA	733	17R	19.1
11/28/00	1415	AA	M80	17R	15.4
11/28/00	1432	SW	737	17R	22
11/28/00	1437	NW	DC9	17R	13.8
11/28/00	1457	DL	733	17R	15.3
11/28/00	1500	AA	M80	17R	16.4
11/28/00	1504	SW	733	17R	14.2
11/28/00	1536	UA	72S	17R	22.5
11/28/00	1537	SW	733	17R	inaud
11/28/00	1544	AA	M80	17R	15.8
11/28/00	1608	SW	733	17R	21.6
11/28/00	1616	UA	733	17R	19.3
11/28/00	1618	CO	M80	17R	18.2
11/28/00	1620	HP	733	17R	23.1
11/28/00	1640	AA	757	17R	17.3
11/28/00	1642	SW	733	17R	18.3

11/28/00	1648	SW	733	17R	22.3
11/28/00	1655	AA	M80	17R	18.4
11/28/00	1700	CO	M80	17R	23.3
11/28/00	1702	AA	757	17R	15.2
11/28/00	1717	SW	733	17R	16.3
11/28/00	1719	TW	M80	17R	13.2
11/28/00	1723	SW	733	17R	24
11/28/00	1731	airborne	767	17R	23.4
11/28/00	1738	AA	M80	17R	13
11/28/00	1750	unknown	M80	17R	28.5
11/28/00	1810	unknown	M80	17R	15.1
11/30/00	1021	SW	737	17R	15.5
11/30/00	1119	SW	733	17R	11.6
11/30/00	1124	CO	M80	17R	14.3
11/30/00	1157	AA	M80	17R	11.47
11/30/00	1201	SW	733	17R	18.3
11/30/00	1207	SW	737	17R	10.5
11/30/00	1216	AA	M80	17R	7.8
11/30/00	1217	SW	733	17R	13.4
11/30/00	1223	AA	757	17R	14.8
11/30/00	1250	CO	M80	17R	8.6
11/30/00	1305	UA	733	17R	inaud
11/30/00	1309	SW	733	17R	18.1
11/30/00	1320	AA	M80	17R	12.2
11/30/00	1334	HP	733	17R	17.3
11/30/00	1337	SW	733	17R	12.6
11/30/00	1339	cargo	72S	17R	16.5
11/30/00	1348	SW	733	17R	20.3
11/30/00	1350	CO	733	17R	14.8
11/30/00	1357	AA	M80	17R	12.4
11/30/00	1402	DL	737	17R	12.9
11/30/00	1410	AA	M80	17R	11.3
11/30/00	1411	UA	733	17R	10
11/30/00	1426	UA	72S	17R	20
11/30/00	1429	SW	737	17R	13.4
11/30/00	1449	DL	733	17R	inaud
11/30/00	1507	CO	M80	17R	10
11/30/00	1536	UA	72S	17R	23.3
11/30/00	1541	AA	M80	17R	10.4
11/30/00	1611	SW	733	17R	23
11/30/00	1620	DL	737	17R	9.7
11/30/00	1622	UA	733	17R	16.3
11/30/00	1624	AA	M80	17R	16.1
11/30/00	1633	SW	733	17R	14.5
11/30/00	1636	AA	M80	17R	16.2
11/30/00	1639	DL	72S	17R	11.8
11/30/00	1644	SW	737	17R	19.5
11/30/00	1647	SW	737	17R	12.5
11/30/00	1650	CO	733	17R	13.6
11/30/00	1654	SW	733	17R	17.3
11/30/00	1702	AA	757	17R	10.3
11/30/00	1703	SW	733	17R	11.8
11/30/00	1724	NW	DC9	17R	13
11/30/00	1731	SW	733	17R	8
11/30/00	1738	Airborne	767	17R	18.9
11/30/00	1744	AA	M80	17R	13.3
11/30/00	1745	AA	M80	17R	9.5
12/4/00	852	AA	M80	17R	15.4
12/4/00	919	CO	733	17R	9.3

12/4/00	924	SW	733	17R	16.3
12/4/00	941	SW	733	17R	14.9
12/4/00	953	SW	733	17R	15
12/4/00	956	AA	M80	17R	21.9
12/4/00	1008	SW	733	17R	12.8
12/4/00	1015	CO	M80	17R	12.8
12/4/00	1045	AA	M80	17R	16
12/4/00	1122	AA	M80	17R	9.6
12/4/00	1127	SW	733	17R	15
12/4/00	1129	CO	M80	17R	14
12/4/00	1144	UA	733	17R	21.6
12/4/00	1148	AA	M80	17R	11.6
12/4/00	1151	SW	737	17R	17.7
12/4/00	1154	AA	M80	17R	14.5
12/4/00	1202	SW	737	17R	14.6
12/4/00	1222	AA	757	17R	17.5
12/4/00	1239	CO	M80	17R	10
12/4/00	1307	SW	733	17R	13.9
12/4/00	1311	SW	733	17R	18.1
12/4/00	1328	AA	M80	17R	15.6
12/4/00	1344	SW	733	17R	22.4
12/4/00	1346	SW	733	17R	15.9
12/4/00	1351	CO	733	17R	14.9
12/4/00	1400	AA	M80	17R	6.5
12/4/00	1402	UA	72S	17R	19.5
12/4/00	1415	UA	733	17R	17.8
12/4/00	1432	SW	737	17R	14.2
12/4/00	1500	DL	737	17R	16.2
12/4/00	1509	CO	M80	17R	6.8
12/4/00	1509	SW	733	17R	10.5
12/4/00	1510	SW	737	17R	18.7
12/4/00	1525	UA	72S	17R	20.1
12/4/00	1535	AA	M80	17R	14.8
12/4/00	1538	SW	737	17R	17.4
12/4/00	1607	SW	733	17R	20.3
12/4/00	1609	CO	M80	17R	15.5
12/4/00	1620	HP	733	17R	18.3
12/4/00	1635	SW	733	17R	23.3
12/4/00	1637	SW	733	17R	16.1
12/4/00	1655	SW	733	17R	19.3
12/5/00	1004	CO	M80	17R	17.3
12/5/00	1008	SW	737	17R	15
12/5/00	1013	AA	M80	17R	14.9
12/5/00	1014	DL	M80	17R	17.7
12/5/00	1119	SW	733	17R	15.9
12/5/00	1134	CO	M80	17R	10.5
12/5/00	1138	AA	M80	17R	19.1
12/5/00	1147	UA	733	17R	inaud
12/5/00	1157	SW	737	17R	14.8
12/5/00	1158	SW	733	17R	13.8
12/5/00	1200	AA	M80	17R	8.4
12/5/00	1203	cargo	727	17R	19.6
12/5/00	1217	AA	757	17R	16
12/5/00	1226	CO	M80	17R	13.8
12/5/00	1235	AA	M80	17R	11.7
12/5/00	1308	SW	733	17R	16.4
12/5/00	1312	SW	733	17R	10.9
12/5/00	1316	AA	M80	17R	10.2
12/5/00	1320	AA	M80	17R	14.8

12/5/00	1327	HP	733	17R	15.4
12/5/00	1329	charter/cargo	72S	17R	11.2
12/5/00	1331	UA	72S	17R	19.1
12/5/00	1337	SW	733	17R	17.1
12/5/00	1342	DL	737	17R	8.4
12/5/00	1345	SW	733	17R	18.8
12/5/00	1351	CO	733	17R	11.3
12/5/00	1357	AA	M80	17R	13.6
12/5/00	1417	UA	733	17R	16.5
12/5/00	1433	SW	737	17R	21
12/5/00	1505	DL	733	17R	12
12/5/00	1506	CO	M80	17R	12.2
12/5/00	1509	SW	733	17R	16.3
12/5/00	1525	SW	733	17R	15.3
12/5/00	1530	UA	72S	17R	18.8
12/5/00	1547	AA	M80	17R	14.5
12/5/00	1551	cargo	72S	17R	11.5
12/5/00	1555	SW	737	17R	16
12/5/00	1611	CO	M80	17R	15.9
12/5/00	1625	UA	733	17R	11
12/5/00	1630	AA	M80	17R	13.8
12/5/00	1634	SW	737	17R	11.3
12/5/00	1645	SW	733	17R	21
12/5/00	1654	AA	757	17R	13
12/5/00	1656	SW	733	17R	14.4
12/5/00	1701	unknown	733	17R	19.5
12/5/00	1711	SW	733	17R	16.6
12/5/00	1715	AA	757	17R	9.8
12/5/00	1740	SW	733	17R	12
12/5/00	1743	unknown	M80	17R	24.6
12/5/00	1759	unknown	733	17R	16.1
12/5/00	1803	unknown	M80	17R	14
12/5/00	1805	unknown	M80	17R	23.6
12/5/00	1807	unknown	M80	17R	8.3
12/6/00	1405	AA	M80	17R	16.3
12/6/00	1429	UA	733	17R	20.7
12/6/00	1447	unknown	737	17R	13.1
12/6/00	1528	unknown	M80	17R	17
12/6/00	1532	UA	72S	17R	15.9
12/6/00	1613	SW	733	17R	18.9
12/6/00	1630	unknown	M80	17R	22.8
12/6/00	1644	DL/SW	737	17R	19.5
12/6/00	1702	SW	733	17R	13.3
12/6/00	1705	SW	737	17R	21.4
12/6/00	1710	unknown	M80	17R	13.8
12/6/00	1715	AA	757	17R	14.1
12/6/00	1721	unknown	733	17R	16.2
12/6/00	1728	AA	757	17R	14.2
12/6/00	1755	unknown	M80	17R	16.5
12/6/00	1810	unknown	M80	17R	17.6
12/6/00	1817	AA	757	17R	10.1
12/6/00	1831	unknown	M80	17R	9.5
12/7/00	1002	CO	M80	17R	12
12/7/00	1027	NW	DC9	17R	8.2
12/7/00	1031	AA	M80	17R	10.6
12/7/00	1114	SW	733	17R	11.3
12/7/00	1122	charter	72S	17R	11.6
12/7/00	1135	AA	M80	17R	8

12/7/00	1139	SW	733	17R	12.2
12/7/00	1147	AA	M80	17R	12.5
12/7/00	1158	SW	737	17R	10.5
12/7/00	1200	SW	733	17R	14.7
12/7/00	1209	AA	M80	17R	7.8
12/7/00	1216	AA	757	17R	18.6
12/7/00	1240	UA	733	17R	10.9
12/7/00	1315	CO	733	17R	15.9
12/7/00	1318	HP	733	17R	12.3
12/7/00	1319	charter	72S	17R	17.4
12/7/00	1330	UA	733	17R	13.7
12/7/00	1337	SW	733	17R	13.5
12/7/00	1347	UA	72S	17R	14.7
12/7/00	1352	CO	733	17R	12
12/7/00	1401	SW	733	17R	13.1
12/7/00	1422	unknown	733	17R	17
12/7/00	1429	SW	737	17R	15.3
12/7/00	1457	AA	M80	17R	11.4
12/7/00	1554	unknown	733	17R	19.1
12/8/00	955	CO	733	17R	13
12/8/00	1002	CO	M80	17R	13.4
12/8/00	1008	SW	733	17R	20.6
12/8/00	1042	DL	M80	17R	17.2
12/8/00	1101	AA	M80	17R	10.9
12/8/00	1109	SW	733	17R	20.6
12/8/00	1131	CO	M80	17R	16
12/8/00	1139	AA	M80	17R	15
12/8/00	1146	AA	M80	17R	12.7
12/8/00	1148	UA	733	17R	15.2
12/8/00	1200	SW	737	17R	15.3
12/8/00	1219	SW	733	17R	14.1
12/8/00	1220	AA	757	17R	15.1
12/8/00	1231	AA	M80	17R	13.9
12/8/00	1237	CO	M80	17R	13.3
12/8/00	1323	SW	733	17R	15.6
12/8/00	1327	UA	72S	17R	20.3
12/8/00	1338	HP	733	17R	16.9
12/8/00	1341	cargo	DC9	17R	17.2
12/8/00	1349	CO	733	17R	16
12/8/00	1351	SW	733	17R	inaud
12/8/00	1353	CO	733	17R	20.6
12/8/00	1403	AA	M80	17R	17.5
12/8/00	1404	AA	M80	17R	13.9
12/8/00	1426	SW	737	17R	13.5
12/8/00	1436	charter	72S	17R	32.9
11/6/00	1443	UA	733	35L	14.3
11/6/00	1448	DL	72S	35L	19.5
11/6/00	1450	DL	733	35L	12
11/6/00	1513	SW	733	35L	19.5
11/6/00	1557	UA	72S	35L	21.9
11/6/00	1612	CO	733	35L	15.5
11/6/00	1614	UA	733	35L	16.6
11/6/00	1647	SW	737	35L	15.3
11/6/00	1649	DL	72S	35L	18.3
11/6/00	1705	SW	733	35L	22.5
11/6/00	1715	AA	757	35L	16.6
11/6/00	1724	SW	733	35L	22.1
11/6/00	1730	SW	733	35L	19.2
11/6/00	1734	SW	733	35L	22.4

11/6/00	1808	SW	733	35L	19.5
11/6/00	1811	DL	M80	35L	15.5
11/6/00	1814	SW	733	35L	17.2
11/6/00	1816	CO/AA	M80	35L	16.9
11/6/00	1822	AA	757	35L	11
11/6/00	1849	SW	737	35L	6.1
11/17/00	1222	SW	733	35L	14.8
11/17/00	1227	AA	M80	35L	10
11/17/00	1231	SW	733	35L	15.2
11/17/00	1244	AA	757	35L	14
11/17/00	1251	charter	72S	35L	25.6
11/17/00	1318	HP	733	35L	23.7
11/17/00	1336	SW	733	35L	13
11/17/00	1338	CO	733	35L	18.7
11/17/00	1347	AA	M80	35L	inaudible
11/17/00	1350	SW	733	35L	22.1
11/17/00	1355	UA	72S	35L	27.5
11/17/00	1358	AA	M80	35L	18.1
11/17/00	1404	CO	733	35L	22.5
11/17/00	1410	CO	733	35L	20.1
11/17/00	1431	AA	M80	35L	17.4
11/17/00	1435	SW	733	35L	20
11/17/00	1453	UA	733	35L	10.8
11/17/00	1506	DL	733	35L	11.5
11/17/00	1520	SW	737	35L	15.7
11/17/00	1528	SW	733	35L	19.5
11/17/00	1601	CO	M80	35L	11.3
11/17/00	1615	SW	733	35L	21.3
11/17/00	1617	HP	733	35L	22
11/17/00	1622	CO	M80	35L	11.1
11/17/00	1634	SW	733	35L	13.5
11/17/00	1637	UA	733	35L	19.1
11/17/00	1642	DL	733	35L	inaudible
11/17/00	1701	CARGO	767	35L	30.1
11/17/00	1708	SW	733	35L	20
11/17/00	1710	SW	733	35L	24.9
11/17/00	1717	AA	757	35L	inaudible
11/17/00	1720	SW	733	35L	20.9
11/17/00	1728	AA	M80	35L	16.7
11/17/00	1750	SW	733	35L	10.2
11/21/00	820	CO	733	35L	13.3
11/21/00	901	cargo	D10	35L	27.7
11/26/00	1252	CO	M80	35L	12.2
11/26/00	1303	SW	733	35L	10.7
11/26/00	1329	charter	72S	35L	13.2
11/26/00	1334	SW	733	35L	15
11/26/00	1336	UA	72S	35L	30
11/26/00	1337	HP	733	35L	23.1
11/26/00	1346	CO	733	35L	15.9
11/26/00	1401	AA	M80	35L	18.2
11/26/00	1407	UA	733	35L	14.8
11/26/00	1413	SW	733	35L	17.6
11/26/00	1450	DL	733	35L	15.2
11/26/00	1531	UA	72S	35L	21.2
11/26/00	1534	Airborne	767	35L	no reverse
11/26/00	1540	SW	737	35L	14.9
11/26/00	1543	CO	M80	35L	17.6
11/26/00	1550	AA	M80	35L	11.4
11/26/00	1600	AA	M80	35L	15.8

11/26/00	1601	SW	733	35L	11.6
11/26/00	1607	UA	733	35L	16
11/26/00	1612	HP	733	35L	23.2
11/26/00	1615	CO	M80	35L	15.6
11/26/00	1628	SW	733	35L	11.7
11/26/00	1635	DL	727	35L	18.1
11/26/00	1651	SW	737	35L	24.2
11/26/00	1659	unknown	DC9	35L	23.1
11/26/00	1703	SW	733	35L	13.1
11/26/00	1712	AA	757	35L	14.5
11/26/00	1721	unknown	733	35L	14.4
11/30/00	951	DL	M80	35L	11.3
11/30/00	1004	CO	M80	35L	7.4
11/30/00	1009	AA	M80	35L	10.7
12/7/00	1504	DL	733	35L	inaudible
12/7/00	1511	CO	M80	35L	13.5
12/7/00	1521	SW	733	35L	23.4
12/7/00	1606	SW	733	35L	11.4
12/7/00	1616	HP	733	35L	17.9
12/7/00	1623	AA	M80	35L	15.9
12/7/00	1625	CO	M80	35L	15.6
12/7/00	1632	AA	M80	35L	15.1
12/7/00	1642	SW	733	35L	14.7
12/7/00	1644	SW	733	35L	12.8
12/7/00	1650	AA	757	35L	11.9
12/7/00	1655	SW	737	35L	10.9
12/7/00	1703	AA	757	35L	9.4
12/7/00	1707	cargo	72S	35L	23.2
12/7/00	1711	UA	72S	35L	16.9
12/7/00	1735	SW	733	35L	15
12/7/00	1744	AA	757	35L	12.4
12/8/00	1508	SW	733	35L	inaud
12/8/00	1514	DL	733	35L	18
12/8/00	1523	CO	M80	35L	inaud
12/8/00	1527	DL	72S	35L	14.2
12/8/00	1536	UA	72S	35L	20.5
12/8/00	1539	SW	733	35L	inaud
12/8/00	1605	SW	733	35L	22
12/8/00	1612	HP	733	35L	inaud
12/8/00	1618	UA	733	35L	inaud
12/8/00	1627	SW	733	35L	22
12/8/00	1643	SW	733	35L	inaud
12/8/00	1656	SW	733	35L	13.9
12/8/00	1700	AA	757	35L	16.6
12/8/00	1712	AA	757	35L	11.1
12/8/00	1729	cargo	767	35L	inaud
12/8/00	1732	TW	M80	35L	9
12/8/00	1736	SW	733	35L	15.4
11/9/00	1248	SW	733	35R	inaud
11/9/00	1322	SW	733	35R	16.3
11/9/00	1333	charter	72S	35R	19.9
11/9/00	1337	SW	733	35R	20.3
11/9/00	1345	pvt jet	3 eng	35R	13
11/9/00	1348	SW	733	35R	16
11/9/00	1350	SW	733	35R	24.3
11/9/00	1351	CO	733	35R	13
11/9/00	1353	DL	727	35R	12.5
11/9/00	1356	DL	737	35R	inaud
11/9/00	1432	AA	M80	35R	13

11/9/00	1444	DL	72S	35R	12.2
11/9/00	1512	NW	DC9	35R	16.1
11/9/00	1521	AA	M80	35R	18.1
11/9/00	1613	SW	733	35R	15.7
11/9/00	1629	DL	737	35R	13.4
11/9/00	1655	SW	733	35R	18
11/9/00	1705	SW	737	35R	21
11/9/00	1708	SW	733	35R	17
11/9/00	1731	NW	DC9	35R	15.1
11/9/00	1746	unknown	M80	35R	13.8
11/14/00	1136	AA	M80	35R	15.9
11/14/00	1138	TWA	M80	35R	12.3
11/14/00	1143	SW	733	35R	15.3
11/14/00	1200	SW	737	35R	19.8
11/14/00	1217	SW	733	35R	12.7
11/14/00	1222	AA	M80	35R	15.9
11/14/00	1314	SW	733	35R	18.2
11/14/00	1333	AA	M80	35R	12.8
11/14/00	1339	DL	737	35R	14.7
11/14/00	1343	SW	733	35R	21.2
11/14/00	1407	SW	733	35R	14.9
11/14/00	1414	AA	M80	35R	9.2
11/14/00	1450	DL	733	35R	18.6
11/14/00	1453	DL	72S	35R	15.7
11/14/00	1536	SW	733	35R	15.7
11/14/00	1554	SW	737	35R	19.1
11/14/00	1633	unknown	737	35R	17.7
11/14/00	1751	unknown	M80	35R	22.3
11/14/00	1758	SW	733	35R	27
11/14/00	1806	AA	757	35R	14.3
11/14/00	1823	AA	M80	35R	26.8
11/14/00	1845	SW	737	35R	19.7
11/20/00	906	AA	M80	35R	17.6
11/20/00	941	SW	733	35R	21.4
11/20/00	1013	SW	733	35R	21.6
11/20/00	1022	SW	733	35R	14.9
11/20/00	1028	DL	M80	35R	21.4
11/20/00	1037	AA	M80	35R	14.4
11/20/00	1105	DL	M80	35R	16.2
11/20/00	1136	TW	DC9	35R	14.4
11/20/00	1145	AA	M80	35R	17.6
11/20/00	1156	SW	737	35R	17.6
11/20/00	1208	AA	M80	35R	14.1
11/20/00	1220	AA	M80	35R	7.9
11/20/00	1229	SW	733	35R	18.5
11/20/00	1315	SW	733	35R	18.8
11/20/00	1332	AA	M80	35R	13.3
11/20/00	1344	SW	733	35R	17.1
11/20/00	1346	charter	72S	35R	28.2
11/20/00	1413	AA	M80	35R	17.5
11/20/00	1447	DL	72S	35R	18.3
11/20/00	1457	NW	DC9	35R	12.4
11/20/00	1506	AA	M80	35R	14.6
11/21/00	903	SW	733	35R	21.6
11/21/00	905	SW	737	35R	13.6
11/21/00	918	AA	M80	35R	14.3
11/21/00	923	SW	733	35R	22.4
11/26/00	1302	DL	72S	35R	18.4
11/26/00	1316	SW	733	35R	17

11/26/00	1339	AA	M80	35R	22
11/26/00	1341	SW	733	35R	17.9
11/26/00	1346	DL	737	35R	7.8
11/26/00	1405	AA	M80	35R	9.9
11/26/00	1415	SW	733	35R	17.8
11/26/00	1427	SW	733	35R	22.8
11/26/00	1436	SW	737	35R	20.8
11/26/00	1459	NW	DC9	35R	18.8
11/26/00	1535	SW	733	35R	21.7
11/26/00	1541	SW	737	35R	19
11/26/00	1634	SW	737	35R	17.3
11/26/00	1651	DL	737	35R	15.5

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 6
1445 ROSS AVENUE, SUITE 1200
DALLAS, TX 75202-2733

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Texas Natural Resource Conservation Commission
Commissioner's Office

Robert J. Huston
Chairman
Texas Natural Resource
Conservation Commission
P. O. Box 13087
Austin, Texas 78711-3087

Dear Chairman Huston,

In response to your request for amplification of the Environmental Protection Agency's (EPA's) comments to the proposed Texas rule on emissions from airport ground services equipment (30 Texas Administrative Code §§ 114.400, 114.402, 114.409), enclosed please find an analysis of the Clean Air Act preemption issues related to that rule. Though this document is intended to clarify the EPA's prior comments, the analysis is based on the rule as it was adopted on April 19, 2000. The analysis concludes that the Texas regulation is not preempted by the Clean Air Act.

I appreciate the efforts of the Texas Natural Resource Conservation Commission to develop a strategy for improving air quality in the State and look forward to continuing to work cooperatively in the future. As you may know, EPA and FAA are engaged in discussions with many stakeholder groups to develop a program of voluntary measures to reduce emissions from the aviation sector. If successful, this initiative will provide reductions in NOX and other pollutants at airports throughout the country. If you need further information, please contact me at (214) 665-2100 or Ben Harrison in the Office of Regional Counsel at (214) 665-2139.

Sincerely yours,

Gregg A. Cooke
Regional Administrator

Enclosure

cc: Duncan Norton, General Counsel, TNRCC
Brian Berwick, Texas Attorney General's Office

I. BACKGROUND

A. Statutory Framework

In 1990 Congress amended the Clean Air Act (CAA) and authorized EPA to establish emissions standards for new nonroad engines and vehicles.[1] CAA sections 213, 216(10), (11). Congress also addressed state regulation of nonroad equipment, and established a statutory structure similar in many ways to the pre-existing provisions on state regulations of new motor vehicles. CAA section 209(e).

Sections 209(a) through (d) addresses state regulation of new motor vehicles. Section 209(a) prohibits any state or its political subdivisions from adopting or attempting to enforce emissions standards for new motor vehicles or new motor vehicle engines. It also prohibits States from requiring certification, inspection, or any other approval relating to the control of emissions from new motor vehicles as a condition precedent to initial retail sale, titling, or registration. Section 209(b) authorizes EPA to waive these prohibitions for the State of California under certain circumstances. Section 209(d) provides that nothing in Part B of Title II of the Act, including section 209, limits the right of States and their political subdivisions to control, regulate, or restrict the use, operation, or movement of registered or licensed motor vehicles. Finally, States other than California may adopt and enforce California's emissions standards for new motor vehicles, once California has received a waiver of preemption under section 209(b). CAA section 177.

Section 209(e) addresses state regulation of nonroad equipment. Section 209(e)(1) expressly prohibits States and their political subdivisions from adopting or enforcing any standard or other requirement relating to the control of emissions from two categories of new nonroad equipment - new engines that are used in construction or farm equipment and are smaller than 175 horsepower, and new locomotives or new engines used in locomotives.

Section 209(e)(2) addresses other nonroad equipment. It does not expressly prohibit state regulation, but instead provides that EPA shall authorize California to adopt and enforce standards and other requirements relating to the control of emissions for any nonroad engines other than those preempted under section 209(e)(1). Section 209(e)(2)(A). The criteria for providing such an authorization are similar to those in section 209(b). Section 209(e)(2)(B) allows any state other than California to adopt and enforce emissions standards for nonroad equipment, and to take such others actions as are referred to in section 209(e)(2)(A), if such standards, implementation, and enforcement are identical to California's standards and two years of lead time is provided. Neither California nor other states are authorized to adopt or enforce emissions standards or other requirements for the farm, construction, and locomotive categories of non-road equipment specified in 209(e)(1). The Act requires EPA to promulgate regulations implementing section 209(e). Finally, section 213(d) of the Act specifies that EPA's standards under section 213 are subject to section 209.

EPA promulgated regulations implementing section 209(e) on July 20, 1994 (59 FR 36969). See 40 C.F.R. Part 85 Subpart Q. In addition, on June 17, 1994 EPA issued an interpretive rule stating, in part, that "EPA believes that states are not precluded under section

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[1] For convenience, the term "nonroad equipment" will be used to refer to nonroad engines and nonroad vehicles.

209 from regulating the use and operation of nonroad engines, such as regulations on hours of use, daily mass emission limits or sulfur limits on fuel." See 59 FR 31306, 40 C.F.R. Part 89, Appendix A to Subpart A. Both of these rules were challenged in the Court of Appeals for the District of Columbia Circuit. *Engine Manufacturers Ass'n v. EPA*, 88 F. 3d 1075 (D.C.Cir. 1996)(*EMA*). The basic issue before the court was the scope of preemption under section 209(e). While all parties agreed that Congress implicitly intended to preempt state action under section 209(e)(2), the scope of this preemption was in dispute. The court held that preemption under section 209(e)(2) extended to both new and non-new nonroad equipment. The court then went on to address "what sorts of regulations the states are preempted from adopting."[2] The court agreed with EPA that "standards" prohibited under 209(e) were quantitative limits on emissions as discussed in *Motor & Equipment Manufacturers Ass'n, Inc. v. EPA*, 627 F.2d 1095 (D.C.Cir.1979) (*MEMA*), cert. denied, 446 U.S. 952 (1980). It also agreed that EPA's interpretation of "other requirements" under section 209(e) was reasonable, limiting them to "ancillary enforcement mechanisms such as certificates and inspections."[3] Finally, the court agreed with EPA that states had the rights to impose the kind of use, operation or movement restrictions on nonroad equipment authorized under section 209(d).[4] EPA's regulations and interpretive rule were therefore upheld, with the exception that the implied preemption of section 209(e)(2) was determined to extend to both new and non-new nonroad equipment.

B. Factual Background

The Texas Natural Resource Conservation Commission (TNRCC) recently adopted requirements for emissions reductions that apply to certain owners or operators of fleets of ground support equipment (GSE), at specified airports. The owner or operator must "demonstrate a reduction of oxides of nitrogen (NOx) emissions" equal to or greater than a specified amount. The amount of reductions that the fleet operator must achieve is determined by calculating a specified percentage of the NOx emissions attributable to the GSE fleet during the 1996 calender year. The level of reductions required increases over time.[5]

The fleet operator is required to submit a plan to the TNRCC that "provide[s] for the implementation of emissions reductions to achieve" the required level of NOx reductions. The plan may include at least two alternatives - "emission reductions measures which are applied to the GSE fleet itself," and "measures which have been achieved elsewhere within the nonattainment area" as long as the measures are creditable in accordance with the TNRCC

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[2] *EMA*, 88 F. 3d at 1093.

[3] *Id.*

[4] *EMA*, 88 F. 3d at 1093-94.

[5] 30 Texas Administrative Code (TAC) section 114.402.

provisions for Emissions Credit banking and Trading.[6] It appears that the plan may also include other alternatives, as the provision states that the plan "may" include these two alternatives. Finally, another alternative is provided to fleet operators, relating to the use of electric powered GSE. If an owner or operator ensures that the GSE fleet is 100% electric powered by a specified date then the fleet operator is exempt from the requirements to submit a plan and obtain the required reductions.[7]

II DISCUSSION

A. Background.

The central question is whether the Texas requirements applicable to fleet owners or operators are "standards or other requirements" preempted under section 209(e). Before applying these terms to the Texas GSE requirements, it is important to understand the scope of state action encompassed by these terms, and to interpret them in the context of related of statutory provisions. "Standards ... relating to the control of emissions from [nonroad equipment]" are implicitly prohibited under section 209(e), while section 209(a) expressly prohibits "standards relating to the control of emissions from new motor vehicles or new motor vehicle engines." These provisions use the same terms to identify the prohibited state action, emissions standards, and they should be interpreted as addressing the same kind of requirement. See *EMA*, 88 F. 3d at 1093 (a "standard related to the control of emissions from [nonroad equipment]" is a quantitative limit on emissions of the kind discussed in *Motor & Equipment Manufacturers Ass'n, Inc. v. EPA*, 627 F.2d 1095 (D.C.Cir.1979) (*MEMA*), cert. denied, 446 U.S. 952 (1980), interpreting emission standard under section 209(a).)

An emission standard under section 209(a) and (e) is a quantitative limit on emissions of a pollutant from an engine, vehicle or piece of equipment. The means for achieving such control are typically through modifying or changing the engine or equipment itself, as compared to controlling or regulating how the equipment is operated in-use. This is the central distinction between emissions standards, which are prohibited under section 209(e), and limitations on in-use operation, which are allowed under section 209(d).

For example, a limitation on the hours of use of a piece of equipment, or a daily limit on the mass amount of emissions permitted from operators of nonroad equipment, would typically be considered an in-use limit on operation authorized under section 209(d). While a daily mass emissions limit is a quantitative limit on emissions, control on emissions may be achieved by limiting or changing the times or mode of operation, and not through modifying the design of the engine itself.

Congress explicitly excluded such use restrictions from the preemption of section 209

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[6] 30 TAC section 114.402(d).

[7] 30 TAC section 114.402(g). For GSE units that are not available for purchase or conversion to electric power, an owner or operator may instead use the lowest emitting equipment to satisfy the electric power provision.

because, among other things, Congress believed states were best situated to regulate such use. "It may be that, in some areas, certain conditions at certain times will require control of movement of vehicles. Other areas may require alternative methods of transportation....These are areas in which the States and local government can be most effective." S. Rep. No. 403, 90th Cong., 1st Sess. 34 (1967). Similar congressional intent was expressed when the nonroad provisions were adopted in 1990. *See EMA,* 88 F. 3d at 1094 n.58.

EPA has adopted a provision interpreting the provisions of section 209(d) to authorize state restrictions on the movement, operation and use of nonroad engines. See 59 FR 31306, 31339, 40 C.F.R. Part 89, Appendix A to Subpart A. The U.S. Court of Appeals for the D.C. Circuit, in reviewing EPA's rulemakings adopting 40 C.F.R. Part 89 and Part 85 Subpart Q, upheld EPA's interpretation that the kind of state restrictions on the use of motor vehicles permitted under section 209(d), such as fuel quality specifications, operational mode limitations, and other measures that limit the use of engines or vehicles, were also permitted for state regulation on the use of nonroad engines and equipment. See *EMA,* 88 F. 3d at 1082, 1094.

The prohibition on state emission standards for aircraft has been similarly interpreted. CAA section 231 authorizes EPA to issue emissions standards applicable to the emissions of air pollutants from aircraft. Under section 233, States are prohibited from adopting or attempting to enforce any "standard respecting emissions of any air pollutant from any aircraft or engine" unless the standard is identical to the federal emission standard. *State of California v. Department of the Navy,* 431 F.Supp. 1271 (N.D. Cal. 1977), aff'd. 624 F.2d 885 (9th Cir. 1980) involved a state regulation of emissions from aircraft test cells. The test cell is a structure used to house an aircraft engines during testing of the engine. The state requirement set limits on the level of emissions released from the test cell. After examining the text and legislative history of this provision, the court interpreted section 233's prohibition on state emissions standards as focusing upon "standards for aircraft engine emissions in a way which implies modification of the engine so as to either prevent creation of certain emissions (via internal alteration) or to prevent those emissions from leaving the engine (via external attachment of antipollution devices, etc.)."[8] Section 233 did not prohibit the state's regulation of test cells, which focused on controlling emissions after they left the engine, and without affecting the structure or performance of the aircraft engines themselves.[9] This interpretation was upheld on appeal, where the Circuit Court held that section 233 did not prohibit state reductions that could be met without affecting the design, structure, operation, or performance of the aircraft engine. If the pollution from the test cells could be abated by means other than modification of the engine, then the state regulation would not be preempted. State regulation would impair the federal interest only where the engine or aircraft would have to be altered to accommodate state law.[10]

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[8] Navy at 1282.

[9] Navy at 1282, 1284.

[10] State of Cal. v. Dept. of Navy, 624 F.2d at 888-9.

Finally, EPA interprets the "other requirements" that are prohibited under section 209(e) as limited to "ancillary enforcement mechanisms such as certificates and inspections." This has been upheld as a reasonable interpretation of an ambiguous statutory provision. See *EMA*, 88 F. 3d at 1093.

B. The TNRCC regulations on GSE fleet operators.

On its own, the requirement to submit a plan that achieves a specified amount of emissions reductions is not an emissions standard or other requirement under section 209(e)(2). It is clearly not an ancillary enforcement provision, such as a certification or inspection provision. A general requirement that fleet operators achieve a specified level of NOx reductions is also not an emissions standard applicable to the nonroad equipment. The fact that the level of required reductions is quantified and is calculated based on the level of emissions generated in-use by the GSE fleet in a prior year does not change the conclusion that assigning a general emissions reductions obligation to a fleet operator does not amount to an emissions standard on nonroad equipment. Similarly, the compliance alternatives available to a fleet operator do not transform the general obligation to achieve a certain quantity of reductions into an emissions standard on nonroad equipment.

The first thing to note is that the fleet operator has several alternatives to show compliance with the reductions requirement. One alternative is to generate creditable emissions reductions elsewhere in the area. This is not an emissions standard on the nonroad equipment itself. It is an alternative that encompasses emissions reductions generated from other sources, as long as the reductions meet certain criteria on creditability.

The second alternative allows a fleet operator to apply "emissions reductions measures" to the GSE fleet. This alternative provides the operator with the flexibility to employ a variety of measures to reduce emissions. It does not mandate a quantified emissions level for the equipment itself, generated by changing or modifying the design of the equipment, which is the hallmark of an emissions standard. This compliance alternative would include measures that reduce emissions by restricting the *use or operation* of the equipment. This could include changes in their hours of operation as well as changes in the patterns of retiring and purchasing new equipment. While a fleet operator would have the option to modify or make changes to the design of their equipment to reduce emissions, this compliance alternative is not limited to this approach.

The third alterative allows the fleet operator to ensure that their fleet is 100% electric powered by a certain date.[11] This is achieved by either converting GSE equipment to electric power or purchasing electric powered GSE. A nonroad engine is by definition powered by an internal combustion engine. CAA section 216(10). An electric powered GSE therefore would

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[11] The electric power provisions in 30 TAC section 114.402(g) states that "in lieu of compliance" with the reduction requirement, an operator may demonstrate that their fleet is 100% electric powered. Also, *see* fn. 7. While this is not technically a compliance alternative under section 114.402(d), for convenience it will be included in the term compliance alternative for purposes of this discussion.

not be considered nonroad equipment. This alterative therefore amounts to a fleet operator deciding to stop using nonroad equipment, and instead either converting the nonroad equipment to electric or purchasing electric GSE, such that the entire GSE fleet is no longer composed of nonroad equipment. This compliance alternative may be seen as completely ceasing the use and operation of nonroad GSE equipment, which would not set an emissions standard for nonroad equipment, but would instead cease the use of such equipment.

The emissions reductions requirements on fleet operators therefore amount to a general obligation to obtain a specified amount of emissions reductions, with several alternatives available to the fleet operator. The alternative to generate creditable reductions elsewhere in the nonattainment area is clearly not an emissions standard on nonroad equipment. The alternative to obtain reductions from the GSE fleet itself does not mandate a specific emissions level that the equipment must achieve, but instead provides the fleet operators flexibility in how they obtain the reductions, including allowing restrictions on use and operation of the equipment. The alternative to demonstrate that the GSE fleet is 100% electric powered may be seen as restricting the use of nonroad equipment by converting or replacing them with other equipment that does not meet the definition of nonroad equipment.

The alternatives for compliance do not transform the general obligation to obtain a specified level of emissions reductions into an emissions standards on the nonroad equipment. The general obligation allows alternatives that are not preempted under section 209.

This conclusion would apply even if, assuming arguendo, one or more of the compliance alternatives were deemed to be an emissions standard on nonroad equipment. The general obligation to achieve emissions reductions, with several alternatives for compliance, does not itself require that nonroad equipment meet an emissions standard, as long as there are viable alternatives for compliance that are not emissions standards on nonroad equipment. Section 209(e) prohibits states from adopting and enforcing an emissions standard on nonroad equipment. If a regulated party has valid alternatives for compliance that are not emissions standards, then the state is requiring a choice among alternatives, and is not enforcing an emissions standard. Even if an option available to a fleet operator would call for modifying the design of the equipment to reduce emissions to specified levels, the fleet operator is not required to take that option. Enforcing a choice among valid alternatives, at least some of which are not emissions standards, does not amount to enforcing a mandatory emissions standard.

On its face, the GSE regulations adopted by TNRCC appear to provide several such valid alternatives that are not emissions standards on the equipment. It follows that the regulations are not emissions standards or other requirements on nonroad equipment, and are therefore not preempted under section 209(e) of the Act.[12]

C. CONCLUSION

Section 209(e) prohibits States and their political subdivisions from adopting or enforcing

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[12] The Texas rulemaking concluded that these alternatives are viable. This conclusion is assumed for purposes of this analysis.

any standard or other requirement relating to the control of emissions from nonroad engines or nonroad equipment. The Texas requirement that owners and operators of airport ground services equipment produce emission reductions equivalent to 90% of the 1996 NOx emissions contributed by GSE is not a standard or other requirement relating to control of emission as that phrase is used under section 209. With the compliance alternatives afforded GSE owners/operators by the State rule, there is no mandated emission standard on nonroad equipment. Therefore, we believe that the Texas regulation is not preempted by Section 209 of the Clean Air Act.

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U.S. Department of Transportation
Federal Aviation Administration

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Washington, D

Donald Zinger
Assistant Director for
Transportation and Air Quality
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, DC 20460

AUG 24

Dear Mr. Zinger:

This letter clarifies the Federal Aviation Administration's (FAA) views concerning the rule adopted by the Texas Natural Resources Conservati Commission (TNRCC) on April 19, 2000, on emissions from airport gr service equipment. Enclosed please find an analysis of preemption issu related to that rule. The analysis concludes that any authority the State o Texas has to regulate airport ground service equipment is exceeded whe that authority is exercised in a manner that would necessarily regulate aircraft operations. The Clean Air Act and Federal Aviation Act preem state regulations that impinge upon aircraft operations and management the navigable airspace. Based upon the data available, the FAA is unabl conclude that the regulation has left fleet operators a choice between suggested, reasonably available alternative means to comply with the TNRCC regulation and the freedom to select measures that do not restri aircraft operations in the future.

The FAA has confidence that the ongoing discussions with the U.S. EP with stakeholder groups to develop voluntary measures to reduce emissi from the aviation sector will be successful in providing reductions at air throughout the country. In the meantime, FAA encourages U.S. EPA a TNRCC to continue to work cooperatively with appropriate airport offi and other affected parties to explore ways to reduce oxides of nitrogen other pollutants at airports that do not impinge upon aircraft operations. If you would like to discuss this matter further, please feel free to contact me at (202) 267-3577 or Daphne A. Fuller in the FAA Office of the Chief Counsel at (202) 267-3199.

Sincerely yours,

Paul Dykeman
Deputy Director
Office of Environment and Energy

Enclosure

cc: Ben Harrison, Office of U.S. EPA Regional Counsel

I. Factual Background

The TNRCC has adopted a rule that would require persons who own or operate ground service equipment (GSE) in the Dallas Ft. Worth (D/FW) ozone nonattainment area at airports having 100 or more air carrier operations per year, averaged over a three year period to "demonstrate a reduction of oxides of nitrogen (Nox) emissions" equal to or greater than the amount specified in the regulation. This includes the four largest commercial airports in the D/FW ozone nonattainment area, Dallas Ft. Worth, Meachem, Alliance, and Love Field airports. GSE is defined to include equipment that is used to service aircraft during passenger and/or cargo loading and unloading, maintenance, and other ground-based operations (excluding equipment used to service general aviation aircraft and military aircraft and equipment that is used during freezing weather such as ground heaters and deicing vehicles). Owners and operators of ground service equipment are required to:

(1) have a 100% electrified fleet by May 1, 2005 or three years after the airport becomes subject to the rule, whichever is later. If a GSE unit is not available for purchase or conversion to electric power then the lowest emitting equipment available may be used instead, subject to the approval of the executor director of TNRCC and U.S. EPA; or

(2) have a plan that provides for emission reduction measures to achieve the phased compliance required by (a), (b), or (d)(generally 20% by 2003, 50% by 2004, and 90% by 2005). The plan may include measures, which are applied to the GSE fleet itself, and measures which have been achieved elsewhere within the nonattaiment area as long as those measures would be creditable in accordance with the Commission's emission banking program.

By letter dated June 23, 2000, to the Chairman of the Texas Natural Resource Commission, the U.S. EPA Regional Administrator for Region 6 clarified earlier U.S. EPA comments concerning the proposed rule. The letter stated that, based upon U.S. EPA's analysis "the Texas regulation is not preempted by the Clean Air Act."

II. Discussion

A. Federal Preemption

Article VI of the United States Constitution provides that the laws of the United States "shall be the supreme law of the Land; . . . any Thing in the Constitution or Laws of any state to the Contrary notwithstanding." Cipollone v. Liggett Group, Inc., 505 U.S. 504, 516 (1992), quoting Art. VI, cl. 2. Since M'Culloch v. Maryland, 17 U.S. (4 Wheat.) 316, 427 (1819), it has been settled that state law that conflicts with Federal law is "without effect." Maryland v. Louisiana, 451 U.S. 725, 746 (1981). Consideration of issues arising under the Supremacy Clause start with the assumption that the historic police powers of the States are not to be superceded by Federal law unless that is the "clear and manifest purpose of Congress." Cipollone, 505 U.S. at 516, quoting Rice v. Santa Fe Elevator Corporation, 331 U.S. 218, 230, (1947). Accordingly, the purpose of Congress is the ultimate touchstone of preemption analysis. Cipollone, 505 U.S. at 516. Preemption is predicated on Congressional intent.

Federal law may supercede state law in several different ways. California Federal Saving and Loan Association v. Guerra, 479 U.S. 272, 280-281(1987). First, when acting within constitutional limits, Congress is empowered to preempt state law by so stating in express terms. Jones v. Rath Packing Company, 430 U.S. 519, 525 (1977). Second, Congressional intent to preempt state law in a particular area may be inferred from a " 'scheme of federal regulation . . . so pervasive as to make reasonable the inference that Congress left no room for the States to supplement it,' because the 'Act of Congress may touch a field in which the federal interest is so dominant that the federal system will be assumed to preclude enforcement of state laws on the same subject,' or because 'the object sought to be obtained by the federal law and the character of obligations imposed by it may reveal the same purpose.' " Pacific Gas and Electric v. State Energy Resources Conservation & Development Commission, 461 U.S. 190, 203-204 (1983), quoting Fidelity Federal Savings & Loan Association v. De la Cuesta, 458 U.S. 141, 153 (1982), Rice v. Santa Fe Elevator Corporation, 331 U.S. 218, 230 (1947). Third, in those areas where Congress has not completely displaced state regulation, Federal law may nonetheless preempt state law to the extent that it actually conflicts with Federal law. Such conflict occurs either because "compliance with both federal law and state regulations is a physical impossibility," Florida Lime & Avocado Growers, Inc. v. Paul, 373 U.S. 132, 142-143 (1963), or because the state law stands "as an obstacle to the accomplishment and execution of the full purposes and objectives of Congress." Hines v. Davidowitz, 312 U.S. 52, 67 (1941).

B. State Regulation Of Aircraft Operations and Use of the Navigable Airspace Is Preempted Under the Clean Air Act, the Federal Aviation Act and Airport Noise and Capacity Act

The authority of the State to regulate aircraft to reduce air pollution is sharply circumscribed under the Clean Air Act, as amended, 42 U.S.C. § 7401, et seq. Section 233 of the Clean Air Act expressly preempts state regulation of aircraft engine emissions. Section 233 provides that "no state or political subdivision thereof may adopt or attempt to enforce any standard respecting emission of any air pollution from any aircraft or engine thereof unless such standard is identical to a standard applicable to such aircraft under this part." 42 U.S.C. § 7573.[1]

Section 233 preempts any action by the State to enforce any standard for aircraft emissions unless the standard is identical to a standard applicable under the Clean Air Act. In other words, the State may only adopt a regulation addressing a particular aircraft emission if it is identical to a Federal standard. If there is no Federal standard, then State action is preempted and the State has no authority to apply a standard. In addition to the explicit prohibition under Section 233, the comprehensive scheme established by Sections 231 and 232 of the Clean Air Act for regulation of aircraft engine emissions by the U.S. Environmental Protection Agency ("EPA") and the U.S. Department of Transportation ("DOT") demonstrates Federal preemption of the field.[2] Under Section 231, the EPA, in consultation with the Secretary of Transportation (to assure safety), establishes national standards for aircraft engine pollutants. EPA must consult with DOT to assure that the standard takes effect after time allowing for the development and application of requisite technology. If DOT finds

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[1] This section has been interpreted in California v. Dept of the Navy, 624 F. 2d 885 (9th Cir. 1980). In that case, the court ruled that the State could regulate U.S. Navy jet engine test cells. These test cells were not considered to fall within the preemption of Section 233 because the test cells were separate and apart from the aircraft engines themselves and could be regulated without necessarily affecting the operation of the aircraft.

[2] See, Washington v. General Motors Corp., 406 U.S. 109, 114 (1972)(Congress has "preempted the field so far as emissions from airplanes are concerned.")

that a proposed standard would create a hazard to aircraft safety, then the DOT may request review by the President who determines whether to disapprove the standard. The EPA has established standards for fuel venting and exhaust emissions for in-use gas turbine airplane engines manufactured after 1984. See 40 CFR Part 87. Under Section 232, the FAA is then responsible for enforcing those standards through the certification process. See 14 CFR Part 34. Based upon this comprehensive scheme there is clearly no room for States to establish or impose any aircraft emission standard not identical to those established by the EPA. When the scheme of regulation of aircraft engine emissions under the Clean Air Act is read together and harmonized with the other aviation statutes discussed below, it is clear that standards under Section 233 refer broadly not just to quantitative emission levels, but to emission reduction targets that necessarily have the direct or indirect effect of restricting aircraft operations.

The Federal Aviation Act, as recodified at 49 U.S.C. § 40103, the regulations implementing it in 14 C.F.R., the Airport Noise and Capacity Act (ANCA), as recodified at 49 U.S.C. § 47521, and the regulations implementing it in 14 C.F.R., preempt the States from regulating in the area of aircraft operations and airspace management. **In a long series of cases,[3] the courts have ruled that neither the States nor their political subdivisions can regulate the manner in which aircraft are operated or the airspace in which the aircraft are operated.** This Federal scheme of regulation is deemed to be pervasive, intensive, and exclusive and is vested solely in the FAA. The court in City of Burbank v. Lockheed Air Terminal[4], expressed concern about the need for uniformity of safe, efficient use of the navigable airspace. It reasoned that to permit curfews and other local regulation of flight operations would increase difficulties of scheduling flights to avoid congestion and concomitant decrease in safety would be compounded.

Congress recently reiterated in ANCA the federal policy against "uncoordinated and inconsistent restrictions on aviation that could impede the national air transportation system." 49 USC 47521(2). Where, as here,

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[3] Allegheny Airlines v. Village of Cedarhurst, 238 F.2d 812 (2d Cir. 1956); American Airlines, Inc. v. Town of Hempstead, 398 F.2d 369 (2d Cir. 1968), cert. denied, 393 U.S. 1017, 21 L.Ed.2d 561, 89 S.Ct. 620 (1969); American Airlines v. City of Audubon Park, 297 F.Supp. 207, aff'd, 407 F.2d 1306 (6th Cir. 1969), cert. denied, 396 U.S. 845, 24 L.Ed.2d 95, 90 S.Ct. 78 (1969); City of Burbank v. Lockheed Air Terminal, 411 U.S. 624 (1973).

[4] 411 U.S. 624 (1973).

Congress has articulated a policy, the most relevant preemption standard appears to be that stated in Rice v. Santa Fe Elevator Corp., 331 U.S. 218, 236 (1947): "The test [of applicability of state laws] is whether the matter on which the State asserts the right to act is in any way regulated by the Federal Act. If it is, the federal scheme prevails though it is a more modest, less pervasive regulatory plan than that of the State." See also, American Airlines v. Hempstead, 272 F. Supp 226, 230, aff'd, 398 F.2d 368, cited in City of Burbank v. Lockheed Air Terminal, 411 U.S. at 628 ("The aircraft and its noise are indivisible; the noise of the aircraft extends outward with the same inseparability as its wings and tail assembly; to exclude the aircraft noise from the Town is to exclude the aircraft...")

Finally, the Airline Deregulation Act of 1978 (ADA), 49 U.S.C. § 41713, prohibits state regulation of aircraft operations. Congress enacted the ADA to "... ensure that the States would not undo federal deregulation with regulation of their own." Morales v. Trans World Airlines, Inc., 504 U.S. 374, 378 (1992). (States' enforcement of attorney general guidelines on air travel industry advertising and marketing practices held to be preempted for having a connection with or reference to airline rates, routes, or services). Section 105 prohibits any State or political subdivision from enacting or enforcing "... any law, rule, regulation, standard, or other provision having the force and effect of law relating to price, routes, or services of any air carrier ...." 49 U.S.C. § 41713(b)(1). The Supreme Court has defined the "relating to" language broadly to mean "having a connection with or reference to airline rates, routes, or services." American Airlines v. Wolens, 513 U.S. 219, 223 (1995), citing Morales, 504 U.S. 374.

D. The TNRCC Regulation

Using its delegated authority under the Clean Air Act and its residual authority, the State of Texas may regulate sources of air pollution to achieve and maintain state and national air pollution standards. We do not here reach the issue of whether the Texas regulation is preempted under Section 209 of the Clean Air Act. We assume here, arguendo, without conceding, that the State of Texas may regulate airport ground service equipment in some manner. However, as discussed above, the State may not impose measures that necessarily regulate aircraft or aircraft operations and interfere with safety and efficiency in management of the navigable airspace. **The central issue here is whether the TNRCC regulation has left owners and operators of GSE equipment the discretion to choose among suggested** procedures and the freedom to choose measures that do not necessarily regulate aircraft operations. See, Air Transport Association v. Crotti, 389 F. Supp. 58 (ND Cal. 1975)(Court upheld state airport noise statute that imposed noise abatement duties on airport proprietors where airport proprietors were left to choose among suggested procedures and were free to choose noise control measures that did not directly regulate aircraft operations). See also, California v. Navy, 431 F. Supp at 1286.

Based upon review of the preamble to the Texas regulations, FAA lacks sufficient data to make an informed judgment that compliance with the Texas regulation is possible without affecting growth in aircraft operations. GSE equipment is necessary to landings and takeoff of aircraft. Aircraft are dependent upon GSE for maintenance, fueling, housing, and in some cases, for movement on the ground as well as a myriad of other activities that are critical to the safety of aircraft and flight preparation. **The availability of reliable GSE equipment is accordingly essential to safe and efficient use of the navigable airspace.**

There is no clear evidence that the emission reduction requirements can be met without reducing total GSE equipment and, in turn, aircraft flights. Electrification will be difficult to implement without affecting operations given the recharging time, battery life, and the need for space for recharging equipment at the airport. Both the phased-in percentage emission reduction alternative and the electrification alternative potentially reduce the availability of GSE during peak periods of airport operation. Limitations on total numbers of GSE available at any given time would create difficulties in scheduling flights and increase congestion and delays.

It is equally unresolved whether the requirement for 100% electrification is feasible given the cost and availability of such equipment or reasonably attainable within the next five years given the infrastructure and electric grid requirements considering cost. TNRCC does not appear to have considered whether "opportunity charging" is practicable. There is little or no evidence that a reliable source of power exists that is adequate to provide power for all necessary GSE equipment and sufficient back-up systems in the event of power outages or disruptions. Although the regulation provides for substitution, the regulation does not articulate the standards that TNRCC and U.S. EPA will use to determine when electric GSE is not available such that the lowest emitting available technology may be substituted.

Based upon information available to date, the emission trading program does not obviate any necessity for fleet operators to limit growth to achieve compliance in the future. There has been no analysis to demonstrate that credits are reasonably expected to be available elsewhere in the nonattainment area. Nor is it clear that the Commission trading program leaves GSE owners and operators the freedom to purchase credits from other nonattainment areas in Texas, such as the Houston area, which has more emissions available for credit. Although we agree with the U.S. EPA letter that the TNRCC regulations may allow owners and operators of GSE to include measures in their plans besides the two enumerated, there is no analysis showing that other viable measures are available to fleet operators.

A case that involves similar facts is San Diego Unified Port District v. Gianturco.[5] In Gianturco, the State sought to require the Port District, as owner of Lindbergh Field, to extend the hours of an existing curfew. The State made extension of the curfew a condition of the variance needed for the permit to continue to operate the airport, which was not in compliance with California noise standards. The Ninth Circuit Court of Appeals held that the State's curfew was federally-preempted because it impinged on airspace management by directing when planes may fly in the San Diego area. The court explained that "Local governments may adopt local noise abatement plans that do not impinge upon aircraft operations." 651 F.2d at 1314. The court reasoned that the State could not use variances, licenses and permits to achieve indirectly what the Supreme Court had precluded in Burbank. **Similarly, assuming arguendo that the State of Texas may adopt plans to regulate ground service equipment, such plans may not indirectly impinge upon aircraft operations.** The State of Texas may not accomplish indirectly that which it is precluded from imposing directly.

The TNRCC regulations may also be determined to be preempted under § 105 of the Airline Deregulation Act of 1978 (ADA), 49 U.S.C. § 41713. To the extent that the TNRCC regulation would effectively require fleet operators to limit operations at airports in Texas, the TNRCC regulations very likely "relate" to air carrier routes in violation of § 41713(b)(1). Whether a fleet operator may take advantage of the flexibility inherent in the Federal deregulatory environment and increase service would appear to depend upon whether the TNRCC regulation indirectly restricts future growth in flights. The statute's proprietary exception, 49 U.S.C. §

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[5] 457 F. Supp. 283 (SD Cal. 1978), aff'd. 651 F. 2d 1306, 1313-14 (9th Cir. 1981), cert. den. 455 US 1000 (1982).

41713(b)(3), does not apply here since the State of Texas is not an airport proprietor.

In support of the conclusion that state regulation of GSE equipment is not federally preempted, in its letter dated June 23, 2000, U.S. EPA posits that the prohibition on state emissions standards under section 233 has been interpreted similarly to the prohibition in section 209. As authority for this proposition, EPA cites State of California v. Navy, supra. However, that case is factually distinguishable. It involved state authority to regulate aircraft engine test cells. The court in that case concluded that state regulation of aircraft engine test cells was not preempted, but did not otherwise define the scope of state authority to regulate aircraft operations. Nor did the court uphold state authority to indirectly regulate aircraft operations through operational restrictions on ground service equipment. Indeed, the reasoning in the case, particularly the opinion of the U.S. District Court, which was cited favorably by the Ninth Circuit Court of Appeals, strongly supports the conclusion that state regulations are federally-preempted to the extent that they necessarily impinge upon aircraft operations. A broad reading of state authority to regulate aircraft operations directly, or indirectly through ground service equipment limitations, would be inconsistent with federal preemption of airspace management and aircraft operations. Compare, Motor Equipment Manufacturers Association v. EPA, 627 F.2d 1095 (DC Cir. 1979), cert. den., 446 U.S. 952 (1980); Engine Manufacturers Association v. US EPA, 88 F.3d 1075, 1094 (DC Cir. 1996)(Section 209 of the Clean Air Act only preempts state regulation to establish quantitative limits on emissions. States have authority to impose restrictions on use of motor vehicles and non-road engines and vehicles, such as limitations on downtown usage).

To interpret the term standards in Section 233 of the Clean Air Act so narrowly as to authorize states to regulate aircraft operations would set a precedent that could lead to a proliferation of restrictions at other airports to control local air pollution. Such a result would be contrary to the concepts of Federal preemption and the comprehensive and pervasive scheme of Federal oversight of the nation's air transportation system enacted by Congress.

This analysis is limited to clarifying the scope of state authority based upon Section 233 of the Clean Air Act, when read together with federal aviation laws. FAA otherwise expresses no opinion concerning the remainder of the analysis in the U.S EPA letter dated June 23, 2000. The FAA reserves the right to revise this analysis should the FAA receive additional, relevant information not heretofore available regarding the TNRCC regulation and alternatives for compliance available under that regulation.

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