**BRITISH AIRWAYS**
**ENVIRONMENTAL AFFAIRS**

# BRITISH AIRWAYS TECHNICAL DOCUMENTS RELATING TO AIRCRAFT OPERATIONS SUPPORTING THE PROJECT FOR THE SUSTAINABLE DEVELOPMENT OF HEATHROW

As part of the UK Government's Project for Sustainable Development of Heathrow (PSDH), British Airways has carried out a number of pieces of work to help identify and characterise a number of aircraft operational practises, in order to inform the modelling process.

British Airways has a policy to help improve the understanding of the environmental impacts of our operations, and is committed to open and honest reporting of these environmental characteristics. In connection with this, we are happy to make publicly available the technical reports detailing a number of studies and analyses carried out as input to the PSDH process.

This document contains the following reports:

1. **"An estimation of the total NOx emissions resulting from aircraft Engine Ground Running at Heathrow airport"**, ENV/KMM/1127/14.18, Jenna C Buttress and Kevin M Morris, British Airways, October 2005.

   This is a brief report of the analysis carried out in 2002 to try to identify the NOx emissions from Engine Ground Running at Heathrow airport, using engine ground run logs and estimated power settings. This is the most precise analysis undertaken of Engine Ground Running emissions at Heathrow and therefore has also been used as the method for estimating these emissions for PSDH.

2. **"Take-off at less than full power"**, WG 3 AEMTG WP10/10, Kevin M Morris, "British Airways/IATA, June 2002.

   Aircraft rarely take-off at full power, though the problem is in identifying the actual power settings used. This report, originally presented at the International Civil Aviation Organisation's (ICAO) Committee on Aviation Environmental Protection (CAEP) Working Group 3, notes the different philosophies behind the calculation of take-off thrust during normal operations, and suggests a method by which they can be estimated using actual aircraft take-off weights as a surrogate.

3. **“Reduced Thrust refinements”** - presentation to Local Air Quality Steering Group, Kevin M Morris, British Airways, February 2003.

   Similar to the CAEP WG 3 working paper, this was a presentation given to the local air quality “Steering Group” justifying the use of lower than full power levels for use in air quality modelling carried out for British Airways. Both reports have been further refined to arrive at the method recommended for PSDH.

4. **“Reverse Thrust Examples from British Airways Operations”**, WG 2 Task Group 4 IP5/7, Kevin M Morris, British Airways/IATA, June 2005.

   As little information is available on the use of reverse thrust during normal aircraft operations, this note was written to provide some information of actual practises. Although the basis of the analysis was the use of FDR information from the world-wide operation of three British Airways types, it has been used by PSDH to identify the characteristics of reverse thrust operation at Heathrow.

5. **“Results from a number of surveys of power settings used during taxi operations”**, EJT/KMM/1126/14.8, Kevin M Morris, British Airways, October 2005.

   Taxi power settings have not been analysed since the emissions certification scheme was originally set up, though some more recent studies have suggested that lower power levels may be more appropriate. This report analyses new information from a survey of IATA carriers, carried out for ICAO, as well as information recorded during taxiing operations by British Airways aircraft.

6. **“Results from two surveys of the use of Reverse Thrust of aircraft landing at Heathrow airport”**, Kevin M Morris and Nita Easey, British Airways/BAA Heathrow, EJT/KMM/1128/14.18, November 2005.

   To ascertain how many operators actually use reverse thrust levels above reverse idle, a survey was conducted for PSDH. This report details the results of that survey to be fed into future modelling.

7. **“An estimation of the tyre material erosion from measurements of aircraft tyre wear”**, EJT/KMM/1131/14.18, Kevin M Morris, British Airways, April 2006.

   Tyres have been identified as a significant source of PM10 emissions, however the actual amount of material worn from aircraft tyres was largely restricted to scaling up measurements from two small aircraft types (BAe 146 and Fokker 100). This report details the results from a number of measurements of new and fully worn tyres from aircraft ranging from A319 to B747-400, so significantly extending the range of information available for PSDH.

8. **"Analysis of aircraft APU emissions characteristics for use in emissions inventories at Heathrow airport"**, EJT/KMM/1134/14.18, Kevin M Morris, British Airways, June 2006.

   Emissions from Auxiliary Power Units (APU), from previous analyses of Heathrow airport, have suggested that APU's contribute a not insignificant portion of NOx from aircraft ground operations. This analysis takes proprietary information received from the APU manufacturers, and distils it into a form which is more accurate than previous methods used. Unfortunately due to the confidentiality required by the manufacturers, and the legal restrictions of the US Export Administration Regulations, the full report is not available for public circulation and only a summary paper is published here.

A number of these reports have also been presented at the appropriate ICAO Committee on Aviation Environmental Protection, Working Group, to aid with the further understanding of the environmental impacts of aircraft operations in this group, as well.

Kevin M Morris
British Airways
Environmental Affairs
14th June 2006
ENV/KMM/1133/14.18

**BRITISH AIRWAYS**
**ENVIRONMENTAL AFFAIRS**

# An estimation of the total NOx emissions resulting from aircraft Engine Ground Running at Heathrow airport


## SUMMARY

An estimate has been made of the total NOx emissions from aircraft during Engine Ground Running at Heathrow airport for the year 2000, using information from the BAA ground running logs for December 1999, and July 2000. The total for the whole of Heathrow airport was approximately 15.6 tonnes per annum, with the majority being emitted in the Engineering Base (excluding ground run pens, 4.2 tonnes per annum), and the two dedicated ground run pens: TE1 "Tristar" pen (3.3 tonnes per annum) and TA9 (6.3 tonnes per annum).

For the period December 2000 and September 2005, BAA recorded statistics for the number of tests per month, show little variation in the number of runs per month for engine runs at ground idle power settings, and a decline of about 25% in "high power" runs above ground idle.


## 1. Introduction

It was considered necessary to look at all sources of aircraft emissions in order to be able to construct a comprehensive inventory of aircraft emissions for use in analysing the impact of British Airways aircraft operations on the concentrations of NOx and $NO_2$ emissions at Heathrow airport. One aspect that had not been considered previously was the impact due to main engine ground running, and this study was carried out as a result.

Engine ground running is an essential part of the operation of any airline. There are a number of reasons for running the main engines on the ground but are generally only recorded as falling into one of the following three categories:

i. Check starts – a check to ensure that the engine will start after minor maintenance action,

ii. Runs at no more than ground idle – function checks to ensure that the engine operates correctly after maintenance action, these include thrust reverser function checks, etc.,

iii. Runs at powers greater than ground idle – function checks where greater than idle power is required to check, for instance the correct operation of certain valves, leak checks, etc.

Regulations on the location and type of engine ground run that may take place are set and policed by the airport operator, HAL, who must give permission for all ground running and keep logs of the runs that have taken place. These rules are published as Operational Standing Instruction OSI/02/03, which replaces OSI/10/97, which was in force at the time this analysis, was carried out.

## 2. Analysis

For this analysis, engine ground run logs were obtained from BAA (HAL) for the whole airport for December 1999 and July 2000. These two months were chosen to be representative of both winter and summer operations in addition and, in addition, July is one of the busiest months for aircraft operations at Heathrow airport. The type of run was identified in the logs as either: Check starts, Ground idle runs or "High Power" runs.

Check starts and idle runs were taken to be conducted at the ICAO "Idle/taxi" power setting equivalent to 7% of "Rated Power" (Foo). This was considered to be conservative as, especially for check starts, a significant portion of the ground run consisted of start-up and shut-down, where emissions of NOx are relatively small.

Engine runs above idle are only allowed in one of the two ground run pens at TE1, the "Tristar Pen", and TA9 on the British Airways Engineering Base. Experience of engine ground running observed during the AEROJET campaigns at Heathrow suggested that the maximum power settings used during ground running rarely exceeded 60% N1 (equivalent to about 30% Foo). This in part was due to the flow dynamics of the pens where hot air re-ingestion and intake distortion provide a significant limitation to maximum power levels, especially in certain wind conditions. For large high power engines, such as the GE90, operations at the highest power settings can also cause the aircraft to climb over the chocks, giving rise to a dangerous situation, so they are also avoided for this reason. As a result, 30% was assumed as a reasonable average power level to assume for engine ground runs above idle.

The only exception to this rule is engine ground runs of Concorde aircraft, which were always carried out in the dedicated Concorde ground run pen, TA5, which were occasionally operated at take-off power, with full reheat, for a short time. This was taken into account in the analysis carried out for these aircraft, however with the small number of aircraft involved, and the corresponding low number of ground runs, the total NOx emissions did not warrant identifying as a specific point source on their own and as a result are included in the "Engine Base" statistics.

As both aircraft type and operator were recorded in the ground run logs, it was possible to identify the engine type bring run by matching the aircraft types and most probable engine fit, using information from the CAA's G-INFO database (www.caa.co.uk/) as well as other databases of aircraft production lists for non-UK operators (www.bird.ch/avmark/library/e_libr00.htm?16,36).

The NOx produced for each run was then calculated by multiplying the run time by the number of engines run along with the fuel flow and NOx EI for the relevant power setting and obtained from the relevant individual data sheets of the ICAO engine emissions databank: (www.caa.co.uk/default.aspx?categoryid=702&pagetype=90&pageid=3825). Total emissions were then summed up over each month for aircraft engine ground runs at each location around the airport, for both British Airways engine ground runs, and the ground runs for other operators.

## 3. Results

Due to the nature of the engine runs, some locations had very few instances of ground runs, and little NOx emitted as a result. In these cases the total NOx emissions were summed up over an area, for input into the model as an area source. Examples are the Central Terminal Area (the stands at Terminals 1, 2 and 3), the Engineering Base (excluding the two Ground Run Pens TA9 and TE1), and the T4 and Cargo area stands. The results from the analysis are presented in Table 1 and illustrated spatially in Figure 1.

| Location | Total Annual NOx emitted for BA operations only | Total Annual NOx emitted for all LHR operators |
|---|---|---|
| **"Point" sources** | | |
| Ground Run Pen TA9 | 6,222 kg | 6,317 kg |
| "Tristar" Pen TE1 | 3,181 kg | 3,323 kg |
| | | |
| **"Area" sources** | | |
| Engineering Base (excluding GR pens) | 1,511 kg | 4,167 kg |
| Central Terminal Area | 928 kg | 1,046 kg |
| Terminal 4 and Cargo | 675 kg | 715 kg |
| | | |
| **Total Airport** | **12,517 kg** | **15,568 kg** |

*Table 1: Estimated total annual NOx emissions from engine ground running at Heathrow airport.*

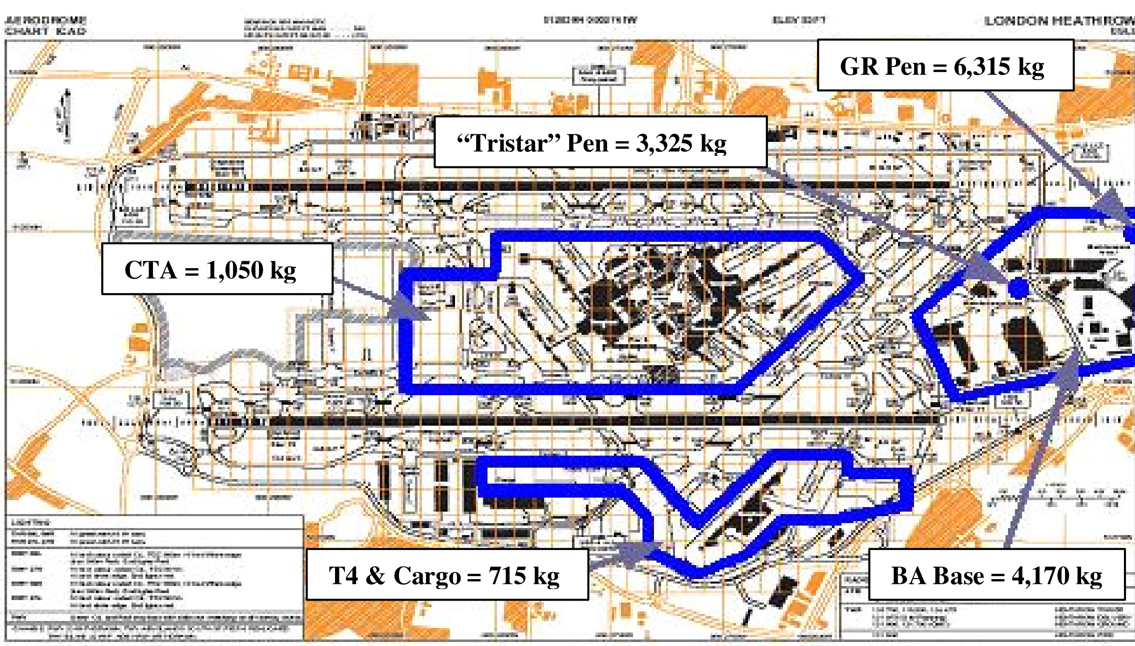



*Figure 1: Estimated total annual NOx emissions by location from engine ground running at Heathrow airport.*

Table 1 gives the NOx inventories, for British Airways alone, and for all operators (including British Airways), showing the amount and location of each source. The map shown in Figure 1 shows the locations of all the sources identified in Table 1 for all operators. From this it can be seen that the NOx from British Airways ground runs accounts for about 80% of those for all operators, though this is not distributed evenly about the airport, with the majority of British Airways ground runs being conducted in the two ground run pens in the Engineering Base.

## 4. Conclusions

The total NOx emissions from aircraft during Engine Ground Running for the whole of Heathrow airport has been calculated as approximately 15.6 tonnes per annum, with the majority being emitted in the airport's Engineering Base (excluding ground run pens, 4.2 tonnes per annum), and the two dedicated ground run pens: TE1 "Tristar" pen (3.3 tonnes per annum) and TA9 (6.3 tonnes per annum). British Airways ground runs contribute about 80% of this total.

For the period December 2000 and September 2005, BAA recorded statistics for the number of engine ground run tests per month, show little variation in the number of runs per month for engine runs at ground idle power settings, and a decline of about 25% for "high power" runs above ground idle.

Jenna Buttress, Environmental Assistant,
Kevin M Morris, Manager Environmental Affairs,
21st October 2005
ENV/KMM/1127/14.18

**ICAO/CAEP/Working Group 3**
**AEM Task Group**
**27-28th June 2002, London, UK**

Take-off at less than Full Power

Presented by
Kevin M Morris, British Airways/IATA

## Introduction

Most operators of most aircraft do not employ full power for take-off. There are three certificated methods for applying power reductions to Take-off power, which are in wide operational use by operators. These are:

1. Reduced thrust/power (also known as flexible thrust),
2. De-rated thrust/power (sometimes referred to as ‘Push-button de-rate),
3. A combination of the two, i.e. reduced thrust/power to a de-rate.

## Reduced power

Essentially an infinitely variable reduction based on reducing the thrust required to the limiting case for the actual take-off weight of the aircraft. It uses the outside temperature as the basis for the application of the reduction, and hence is called the “assumed Temperature” method. In practise the data is usually provided in steps of e.g. 2 or 4 °C, so a more stepped reduction actually occurs. Airworthiness regulations restrict the maximum amount of reduced power allowed to a 25% reduction.

## De-rated power

This is a single reduction to a fixed power setting lower than maximum. It is applied regardless of take-off weight up to the performance limited, or “regulated” take-off weight (RTOW), for the de-rated power setting. Above this RTOW, full power must always be used.

## Reduced power to a de-rate

Where the actual take-off weight is significantly below the RTOW, it may be possible to reduce the take-off power setting even lower by employing a reduced power technique to a de-rated power setting. Reductions of 25% to the de-rated power level, are then available.

## Applicability

The use of reduced or de-rated power is available whenever the actual take-off weight of the aircraft is below the performance limited, or regulated take-off weight (RTOW).

Most aircraft types are able to use at least one of these methods, though it is generally not available for the following types:

Small biz-jets
Turboprops (though not all)
Concorde

The results of a number of surveys suggests that most operators favour the "reduced power" technique.

<u>Limitations</u>

How much reduction can actually be applied depends on a number of factors, some of which are:

<u>Meteorological</u>: e.g. Wind, pressure, temperature, etc.

<u>Airport:</u> e.g. Runway distances/slope, obstacles, state, etc.

<u>Aircraft:</u> e.g. Design, configuration, Vmc, Vmu, etc.

<u>Procedural</u>: e.g. BFL, improved climb, MMEL items, flap setting, etc.

Reduced (and sometimes de-rated) power is usually prohibited when:

1. The runway is icy/slippery, or contaminated with standing water slush or snow,
2. The MMEL requires full, or a minimum power setting to be used,
3. Wind shear or marked surface temperature inversion is believed to be present.

Some examples of power reductions for British Airways aircraft at Heathrow airport, are attached. Heathrow airports runways are significantly long enough to not present a limitation to the take-off weight of most aircraft types in normal operations, so there is normally an opportunity to use some type of power reduction.

The power setting presented here, are the maximum recorded, by the Flight Data Recorder, on the take-off roll until wheels off.

---End---

## Power Reduction - Methods

- Three methods:
  - Reduced/Flexible Power
    - Most common, using "Asumed Temperature" method
  - De-Rated Power
    - Fixed Reduction
  - Combination of the two:
    - i.e. Reduced power to a Derate.

## Power Reduction - Applicability

- Most aircraft types, but in general:
  - NOT Biz-jets
  - NOT Turboprops
  - NOT Concorde
- Most operators use reduced thrust
- Common procedure - Manufacturers
- Approved by Airworthiness Authorities

## How much reduction?

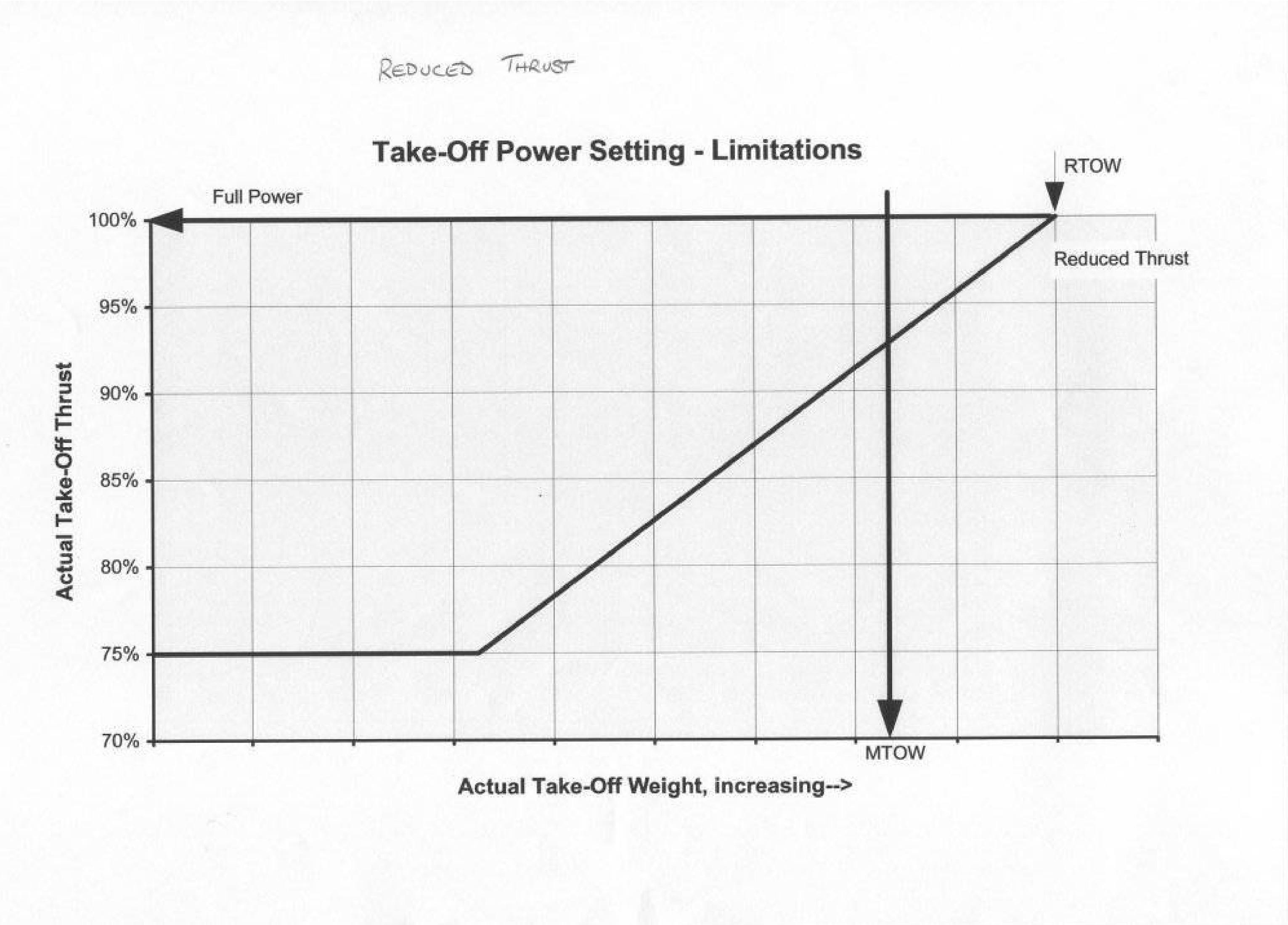
- Depends on:
  - MET
    - Wind, pressure altitude, OAT
  - Airport
    - Runway distances/slope, obstacles, condition
  - Aircraft
    - Design, performance, flap, Vmu, Vmc, etc.
  - Procedure
    - BFL, improved climb, MEL items, etc.

Prohibited when:

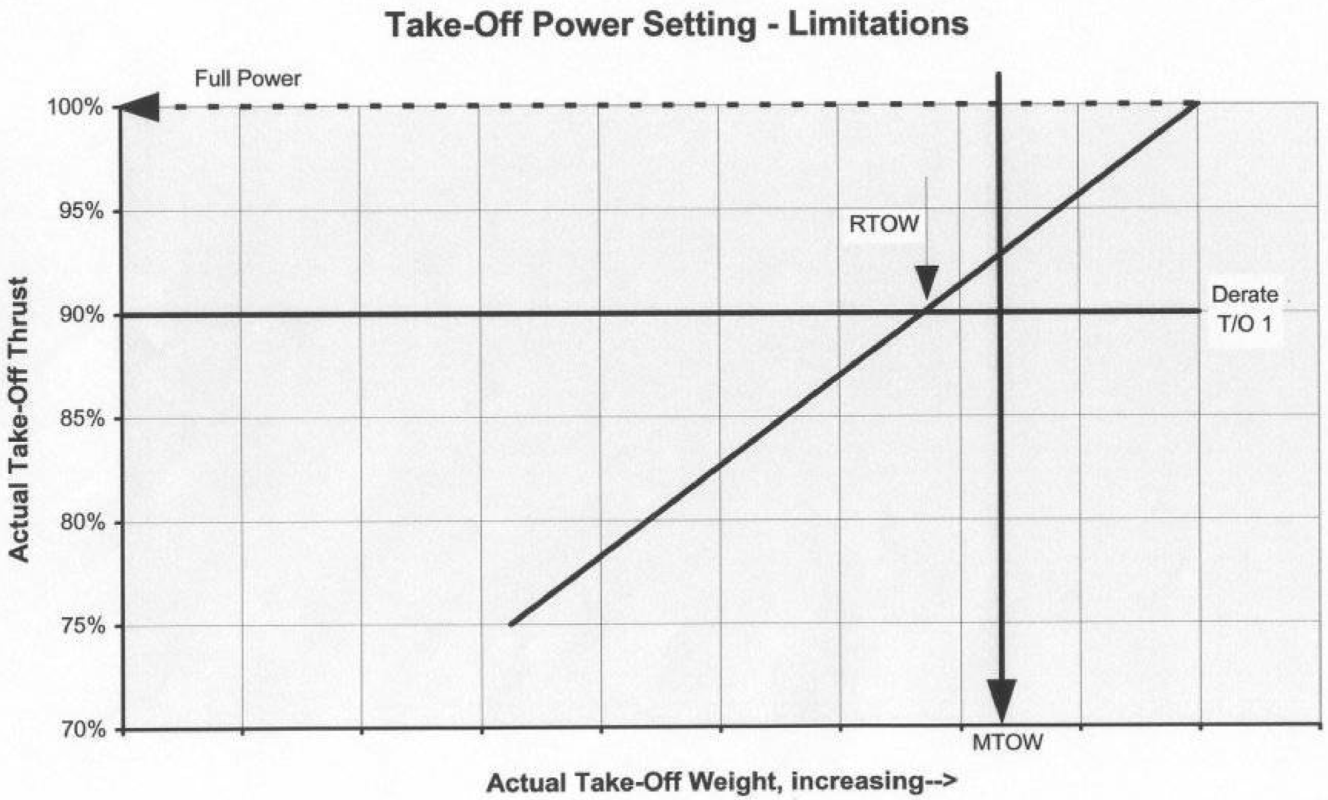
1) R/w is slippery or contaminated with standingwater, slush or snow.

2) MMEL requires full or higher power to be used. (767 plot).

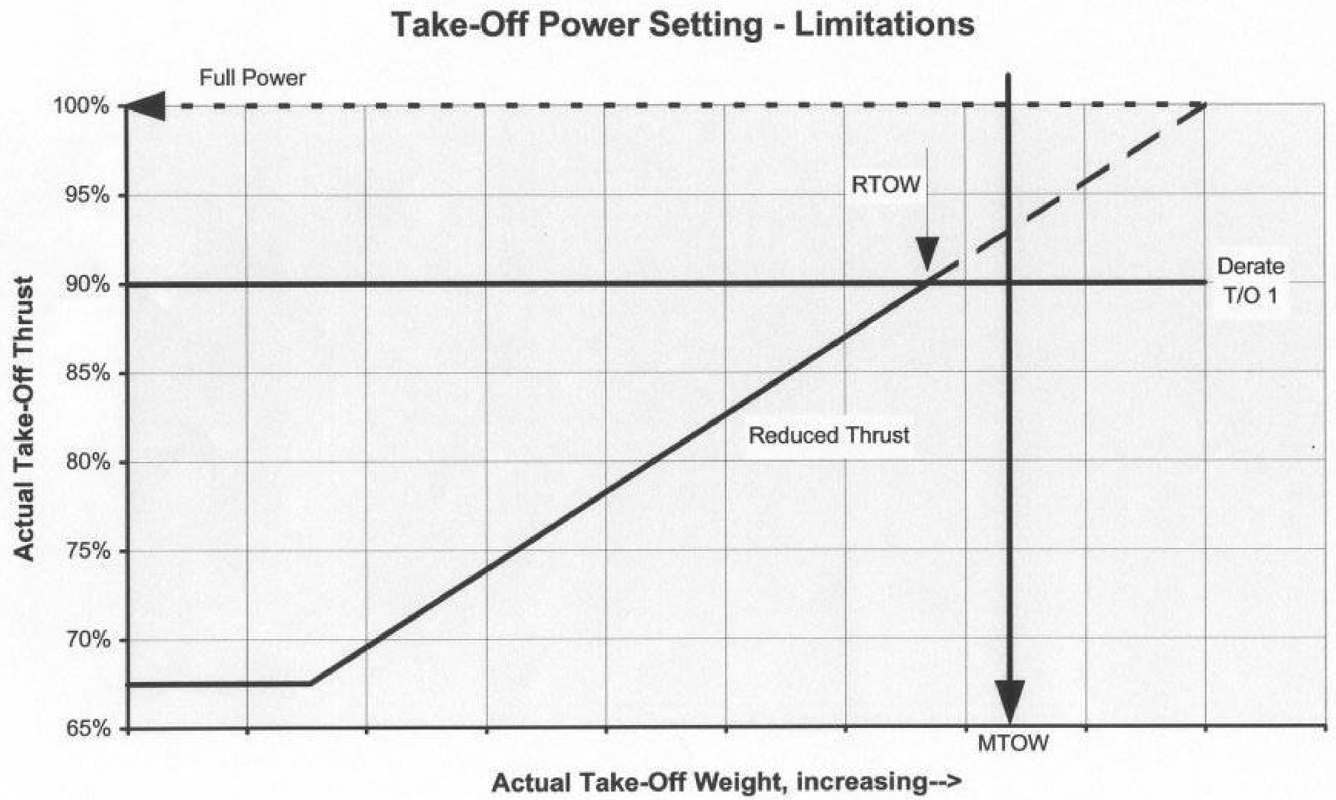
3) Wind shear or Surface temperature inversion >1°/100ft is believed to be present.


REDUCED THRUST
Take-Off Power Setting - Limitations
Full Power
RTOW
Reduced Thrust
100%
95%
90%
85%
80%
75%
70%
Actual Take-Off Thrust
MTOW
Actual Take-Off Weight, increasing-->

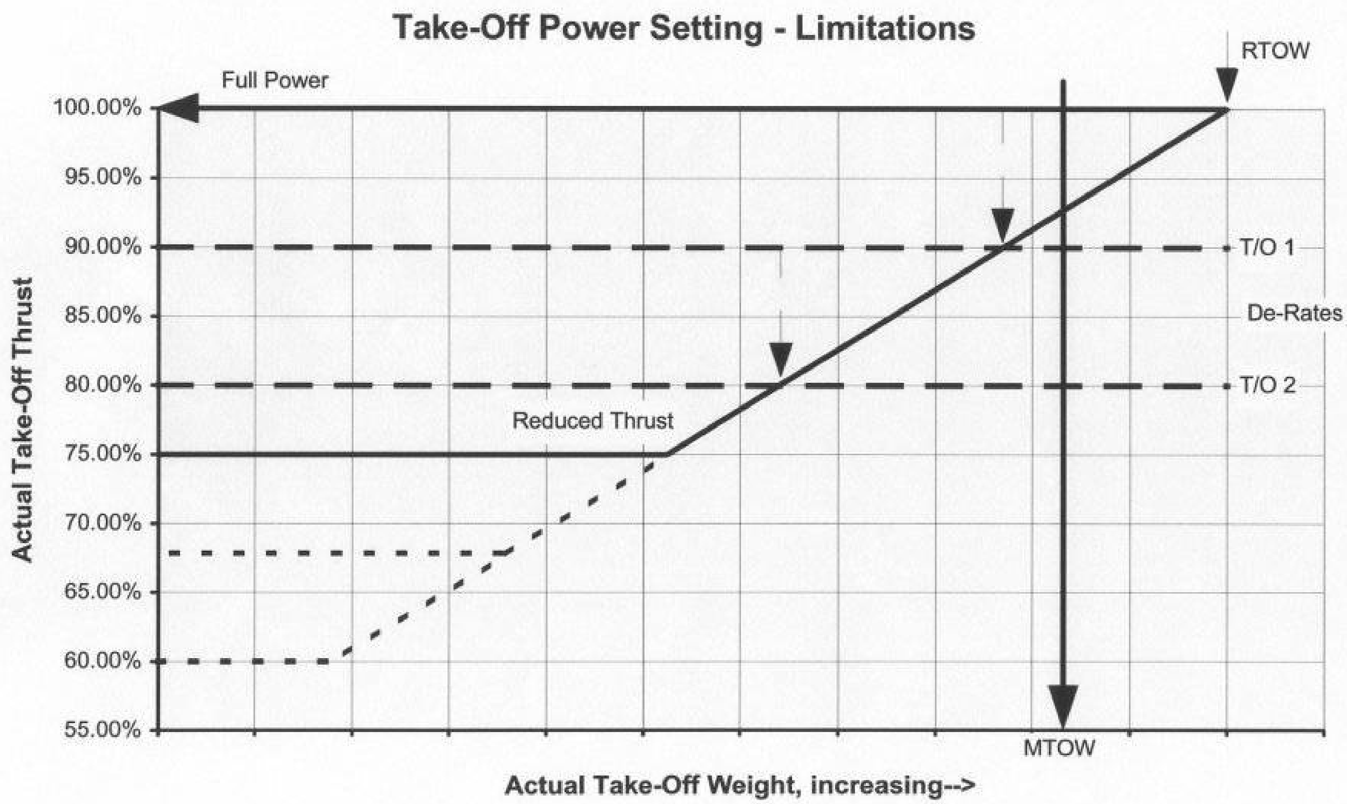
DE-RATE THRUST

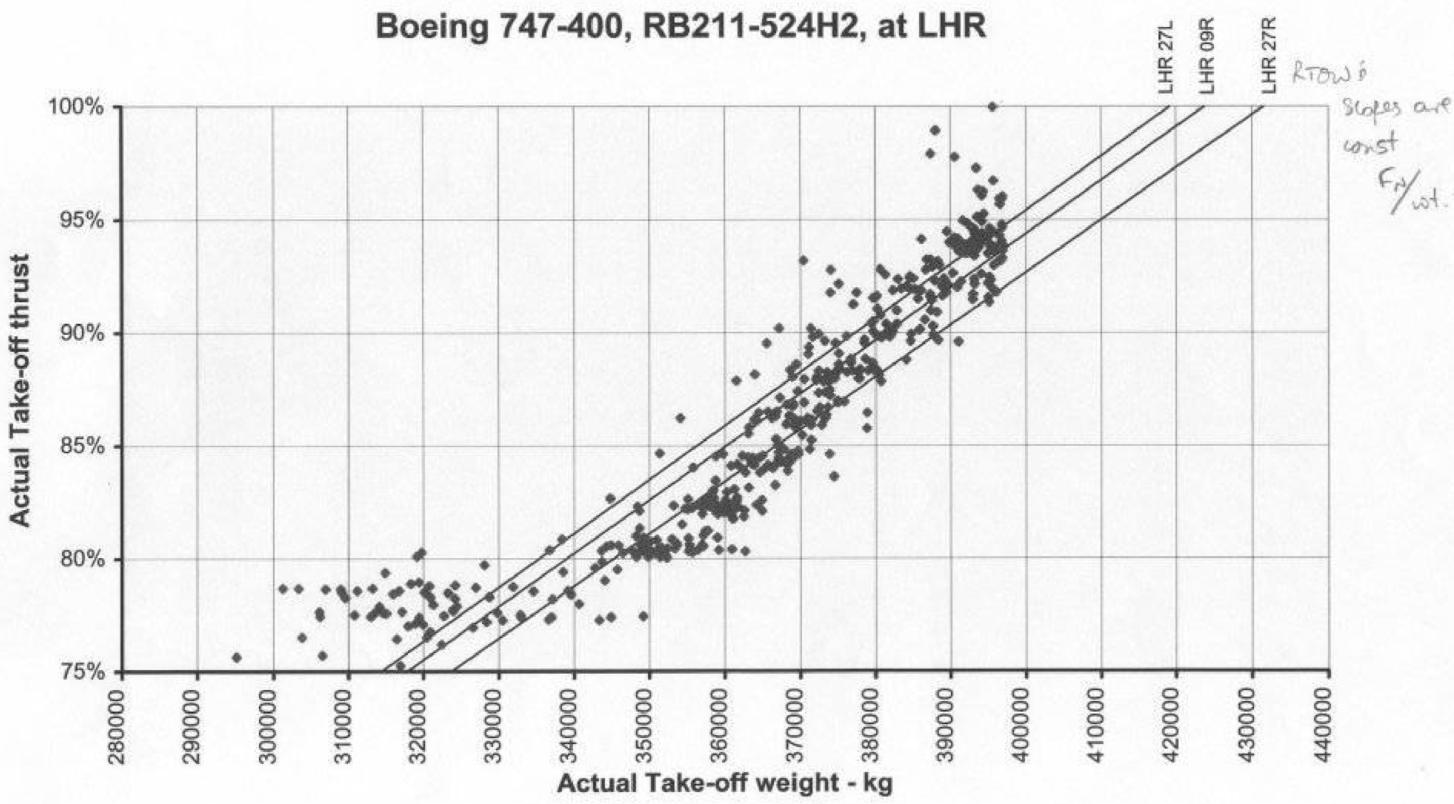


REDUCED THRUST TO A DE-RATE

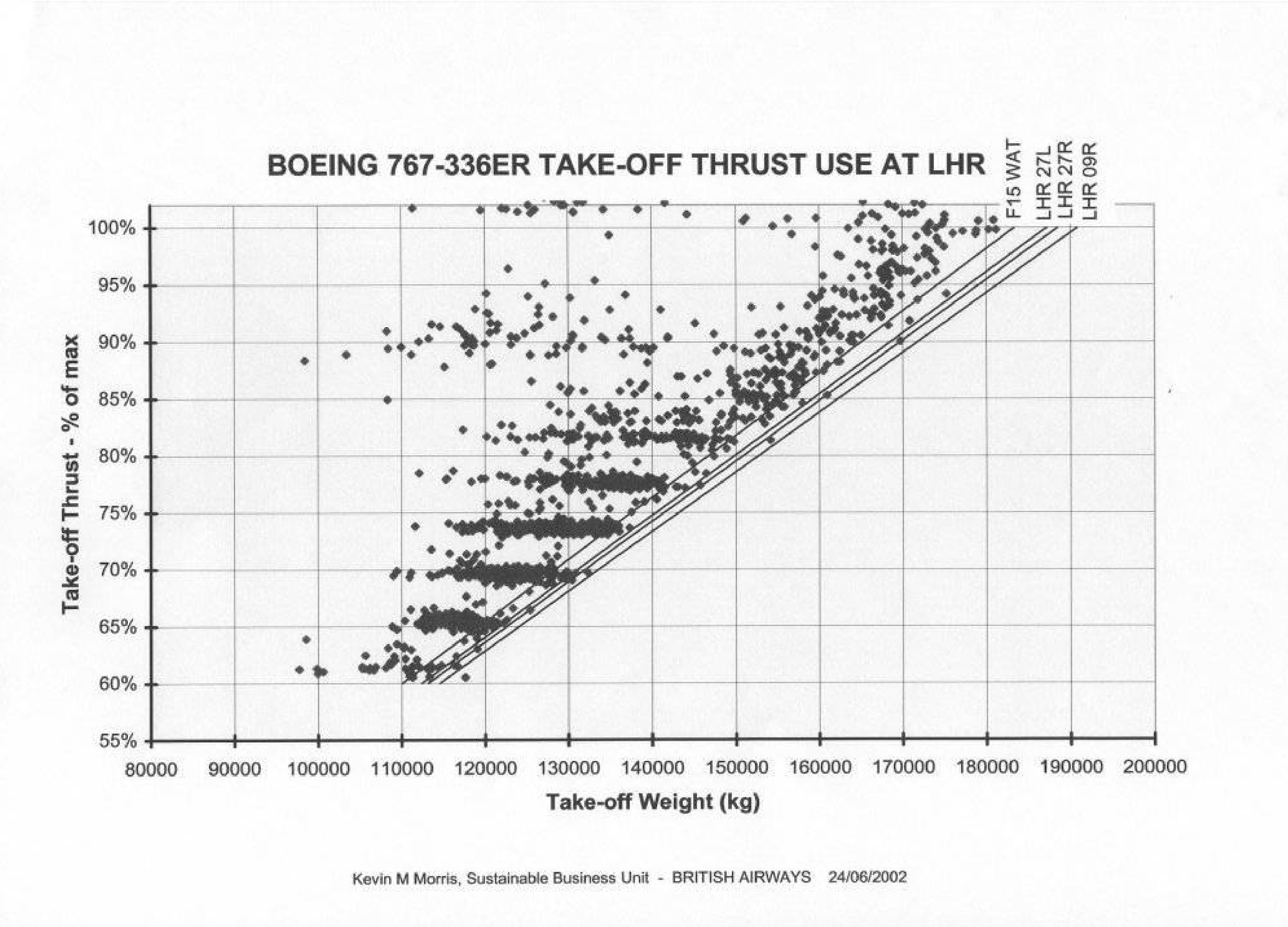


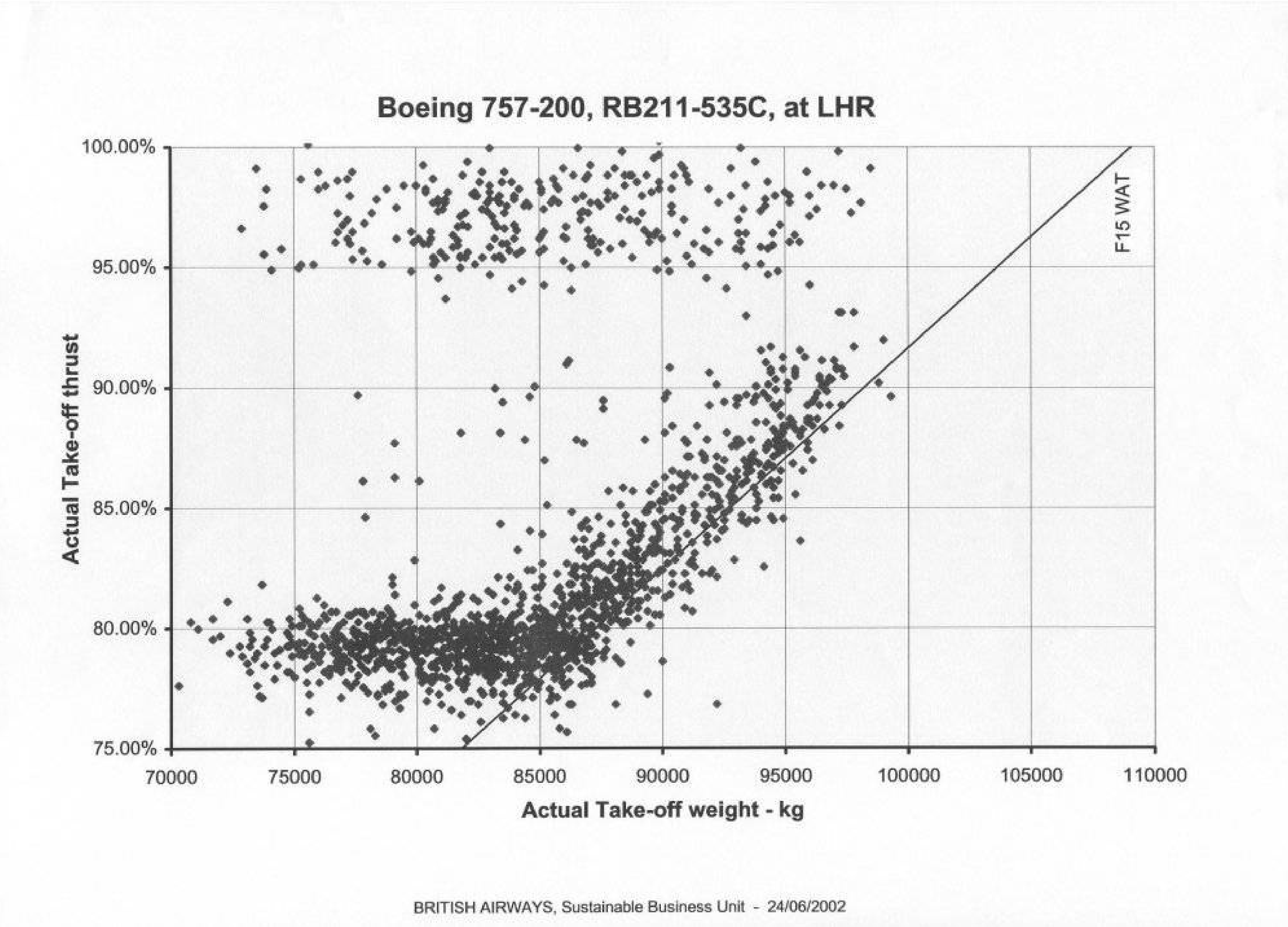
60% (i.e. 40%) POWER IS POSSIBLE

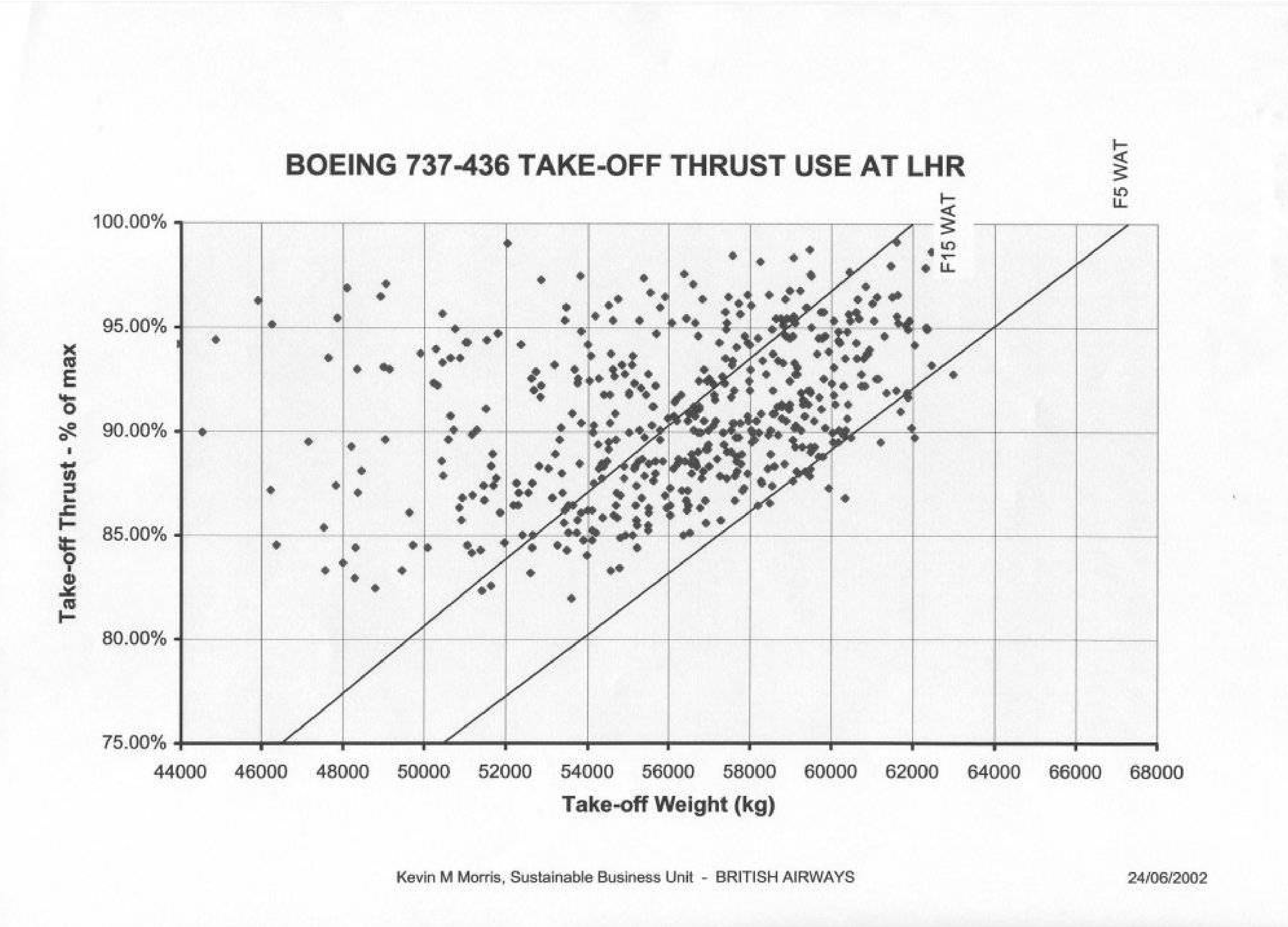





BRITISH AIRWAYS, Sustainable Business Unit - 21/06/2002


BOEING 767-336ER TAKE-OFF THRUST USE AT LHR
F15 WAT
LHR 27L
LHR 27R
LHR 09R
Take-off Thrust - % of max
100%
95%
90%
85%
80%
75%
70%
65%
60%
55%
80000
90000
100000
110000
120000
130000
140000
150000
160000
170000
180000
190000
200000
Take-off Weight (kg)
Kevin M Morris, Sustainable Business Unit - BRITISH AIRWAYS 24/06/2002


Boeing 757-200, RB211-535C, at LHR
Actual Take-off thrust
100.00%
95.00%
90.00%
85.00%
80.00%
75.00%
70000
75000
80000
85000
90000
95000
100000
105000
110000
Actual Take-off weight - kg
F15 WAT
BRITISH AIRWAYS, Sustainable Business Unit - 24/06/2002


BOEING 737-436 TAKE-OFF THRUST USE AT LHR
Take-off Thrust - % of max
100.00%
95.00%
90.00%
85.00%
80.00%
75.00%
44000
46000
48000
50000
52000
54000
56000
58000
60000
62000
64000
66000
68000
Take-off Weight (kg)
F15 WAT
F5 WAT
Kevin M Morris, Sustainable Business Unit - BRITISH AIRWAYS
24/06/2002

# Reduced Thrust refinements

A presentation to the Local Air Quality Steering Group

Kevin M Morris
Manager Environment, British Airways,
14th February 2003

# Original assumption:

All aircraft, regardless of type and operating procedure - 100% power for take-off.

- Doesn't happen in reality.
- Pessimistic - grossly overestimates NOx.
- Feeds through to $NO_2$ concentration overestimate for LAQ.
- Skewed picture for source apportionment.

# First refinement (BEAMAP)

All aircraft, - 100% and 85% power for take-off (where known), 100% power otherwise.

- Doesn't happen in reality, but closer.
- Conservative - still overestimates NOx.
- Not all aircraft types covered.
- Still overestimates aircraft contribution to $NO_2$ concentrations.

# Second refinement (inventory c2003)

<u>All aircraft, type specific (conservative) reduced power for take-off.</u>

- Much closer to reality.
- Regulatory/ aircraft performance basis.
- Covers nearly all aircraft types.
- Still conservative - overestimates NOx and $NO_2$ conc’s, but much more realistic.

# Legislative restrictions:

- **100%** thrust maximum.
- **75%** thrust minimum (nominally - can be lower to 60% absolute minimum).
- 100% thrust required for performance limited Take-off Weight (RTOW).
- RTOW is highest weight allowed, but not readily available, so use MTOW.

# “Proposal” for BA aircraft

- MTOW’s known for BA aircraft types.
- Weight distribution known for BA aircraft.
- Reduced thrust line follows a constant power/weight ratio.
- 75% minimum except: Concorde (100%), and 767 (60%).

# “Proposal” for other operators?

- For aircraft types similar to BA, use BA data.
- For aircraft types not operated by BA, use nearest similar (no. of engines, weights, etc.), and add a “pad” of 5%.
- Much more realistic, but still retains a level of conservatism.

# Future work:

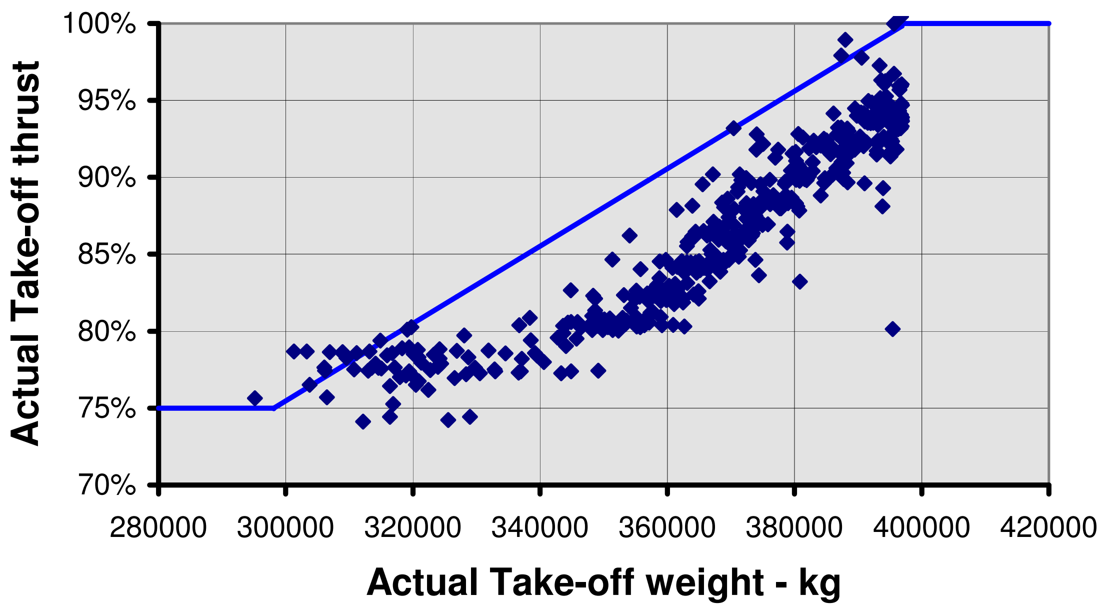
- Slope appears to work well and is justified on technical grounds.
- Estimating RTOW is the major problem.
- May be possible from published MTOW, SLS thrust (ICAO Foo), and R/w length.

<u>BUT</u>

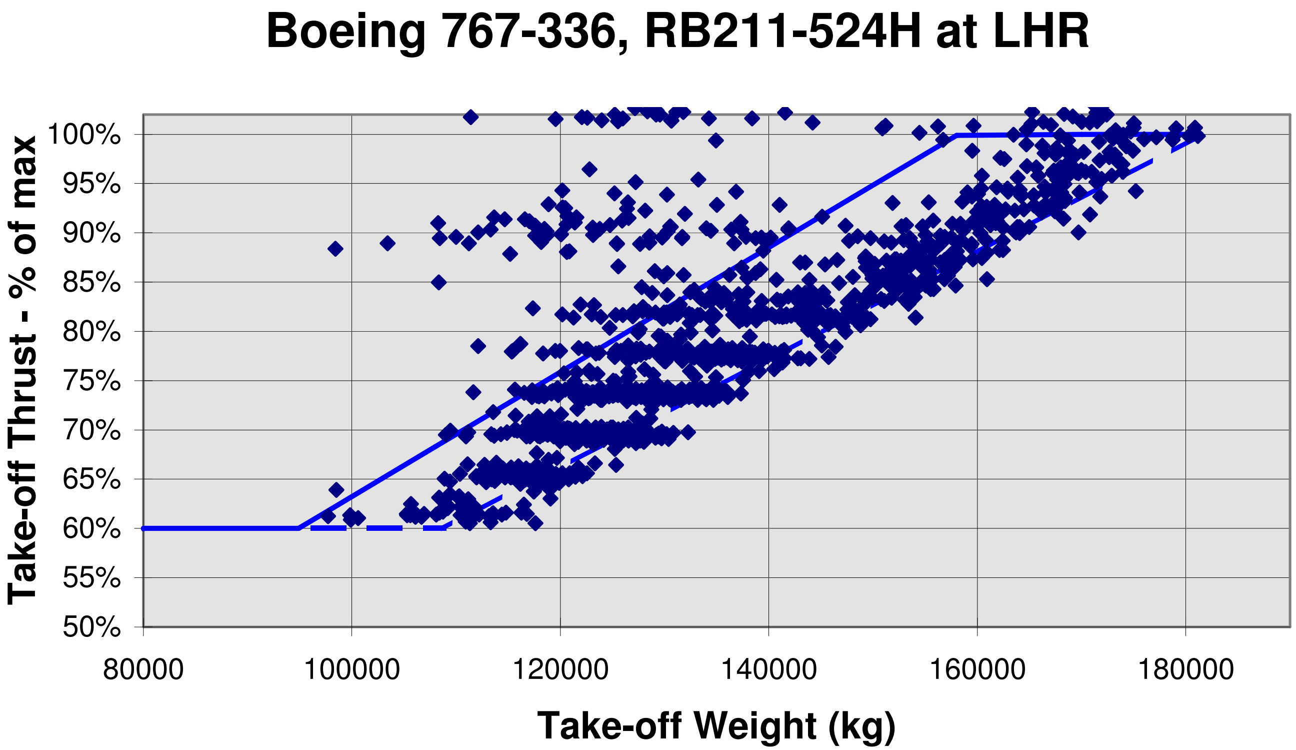
- Long, tedious job - don’t hold your breath!

# How it compares: B747-400

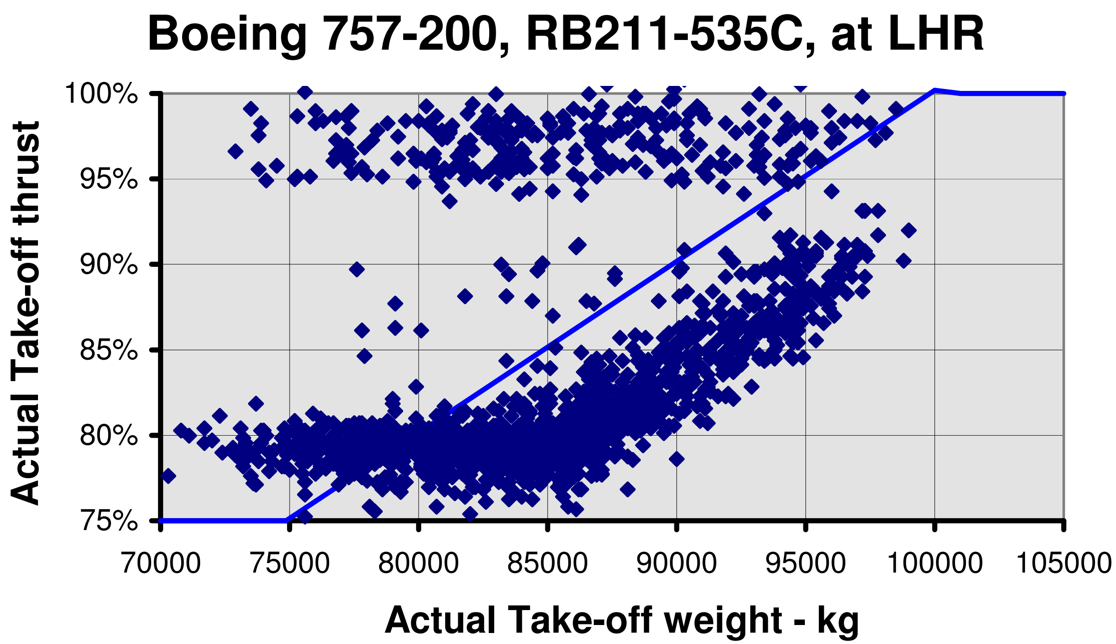
Boeing 747-400, RB211-524H2, at LHR



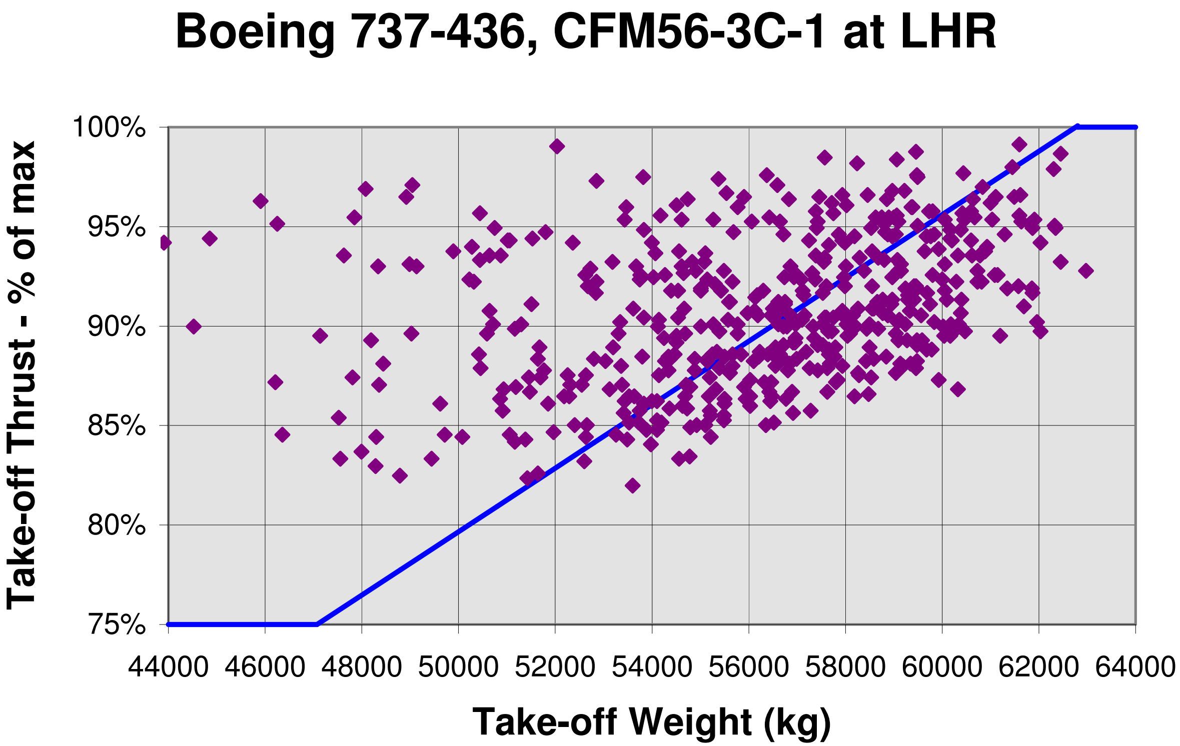
# How it compares: B767-300



# How it compares: B757-200



# How it compares: B737-400



**ICAO/CAEP/Working Group 2**
**Task Group 4**
**6-8th June 2005, Athens, Greece**

Reverse Thrust Examples from British Airways Operations

Presented by
Kevin M Morris, British Airways/IATA

## Introduction

Little information is publicly available on the use of reverse thrust during normal operations; specifically on times power settings and frequency of use. This is often seen as an omission when evaluations of emissions, especially NOx, for local air quality assessments are made. In these cases, non-validated estimates have to be made, out of necessity.

This note is intended to provide some information for operations of three British Airways types (Boeing 747-400, 767-300 and 777-200), and should be seen as complimentary to information presented to Working Group 2, by Unique, Zurich airport, for operations of Swiss.

## Frequency of use

The information presented in this information paper, was obtained from the quick access flight data recorder (QAR), which are fitted to all British Airways aircraft. A computer programme, called SESMA, originally developed to monitor and capture "events" recorded by the QAR which fell outside "normal" pre-set parameters, the information then being fed back into the training programme to promote better airmanship. For this note, the SESMA programme was used to record the maximum level of N1, the engine fan rotational speed, during the ground roll following touchdown. This was carried out for a period of approximately 2 weeks, which was long enough to record what was considered to be a representative number of flights, and coincided with the winter operation in the northern hemisphere.

The results for three types are given in figures 1, 2 and 3, and show the maximum N1 speed recorded during the reverse thrust phase. It should be noted that idle settings for the engines involved, occur in the range 20% - 30% N1, and therefore the majority of records are for an idle power setting. Using the "Boeing fuel flow" method, the information for the Boeing 777-200 type has been recalculated to present the same information as a percentage of the ICAO certification schemes "Rated Output", Foo, in figure 4.

Reverse thrust profile

An example of the engine power settings for a single B777-236ER arrival at Heathrow airport, are shown in figure 5. The plot shows the final phase of a continuous descent approach (CDA) from 3,500 ft aal. The displayed parameters are the radio height trace, the individual engine N1 speeds, and values of Foo, again derived using the "Boeing fuel flow" method.

For the airborne phase, the increases in power setting are evident with both increases in flap setting and lowering of the undercarriage, to a final value of about 30% Foo (60% N1), when the aircraft remains in the final landing configuration with undercarriage locked down and land flap 30 set. The throttles are then retarded to the idle setting during the landing flare, and the engines are still spooling down at the point where the aircraft touches down on the runway.

The reverse thrust phase can be seen clearly in figure 6, where the time baseline has been enlarged, and shows that the thrust reversers are deployed as the engine is still spooling down. During the reverser deployment, there is a brief increase in N1 to approximately 40% (which would be the level recorded in figure 3), but no associated increase in fuel flow and hence value of Foo, the engine continues to spool down to idle at approximately 3% Foo (20% N1). The reverse thrust is then cancelled after an elapsed time of about 35 – 40 seconds, and the rest of the ground roll and turn-off from the runway down a rapid exit turnoff (RET), continues at idle power.

Taxi-in profile

For the remainder of the taxi-in to the terminal, both engines were left running at the idle power setting (3% Foo, 20% N1), apart from two occasions when power was applied to a level of about 10% Foo (32% N1), and 12% Foo (36% N1) for approximately 10 seconds on each occasion. The first of these applications of power was to keep the aircraft rolling when turning round a sharp 90° turn onto the inner taxiway to the north of Terminal 1 at Heathrow; the second was an example where a "pulse" of power was used to ensure that the aircraft taxied at an increased speed to cross the active southern runway (09R/27L), which was being used by departing aircraft, on the way to Terminal 4. These are both examples of what is often referred to a "breakaway" thrust levels for this aircraft under these conditions.

It should be noted that the details of this flight have been used to show an example only of the levels of power used for this aircraft during arrival at its home base. This flight was chosen specifically because it was experienced by a number of WG2 TG4 members, and no check has been made to see if it is representative of all 777-200 flights, or normal operations. However, no special routine was followed by the operating crew, who were not aware that this was to be used in this way, and the flight has been used to show an example of reverse thrust use, and the thrust levels required to cross an active runway.

Furthermore, this flight arrived at a time outside of the night period at Heathrow, when no special restriction or request regarding the use of reverse thrust was in force, and was onto a "dry" runway at one of the busiest times of the day for arrivals at Heathrow. As a result, it has been considered as an example of a "normal" operation of this aircraft type within British Airways service.

## Conclusions

Levels of reverse thrust power used for a sample of three aircraft types for British Airways worldwide operations. The survey has concluded that reverse thrust at levels above idle power, have been recorded far less frequently than has previously been assumed, with approximately 6% of Boeing 747-400 arrivals, 13% of Boeing 767-300 arrivals, and 3% of Boeing 777-200 arrivals using power levels above idle. This was for operations during winter in the northern hemisphere, where the carrier's main base of operations is situated.

Further analysis of a single flight, has suggested that for the Boeing 777-200 at least, the period of reverse thrust operation was limited to about 40 seconds, with the thrust profile following the normal spool-down from approximately 30% Foo to idle with a brief delay of between 1 – 2 seconds at 13% Foo.

Additionally, for this aircraft, the trace suggests that the approach power settings are generally lower than that used for the ICAO aircraft engine emissions certification scheme, with only the last 2 minutes coinciding with 30% Foo. The idle power settings for these engines also appear to be much lower than the 7% used for certification, at a value close to 3%. This is consistent with other surveys (Brooke 1995) that show idle power settings in the range 3% - 5% Foo for a number of engine types.

During taxi-in, the analysed flight contained two events where a brief excursions in power to just above10% Foo, consistent with an increase in power to turn through a sharp 90°, and the second to cross an active runway. In both occasions the elevated power lasted for about 10 seconds duration, including spool-up and spool-down to idle.

This information paper is complimentary to information provided by Unique, Zurich airport that contained information for operations of Swiss.

## References

BROOKE, A. S., CAVES R.E., JENKINSON L.R., Methodology for Assessing Fuel Use and Emissions of Aircraft Ground Operations, Loughborough University of Technology, 1995.

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**B747-436 Maximum N1 Power settings recorded during Reverse Thrust operation**

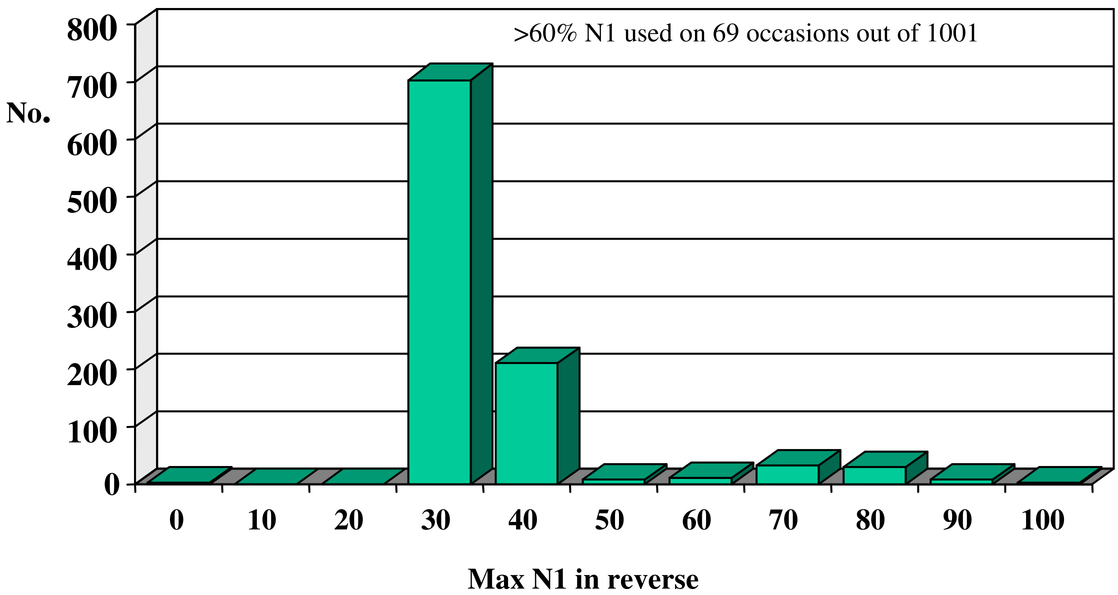


Figure 1. Maximum Reverse Thrust (N1%) use - Boeing 747-436

**B767-336 Maximum N1 Power settings recorded during Reverse Thrust operation**

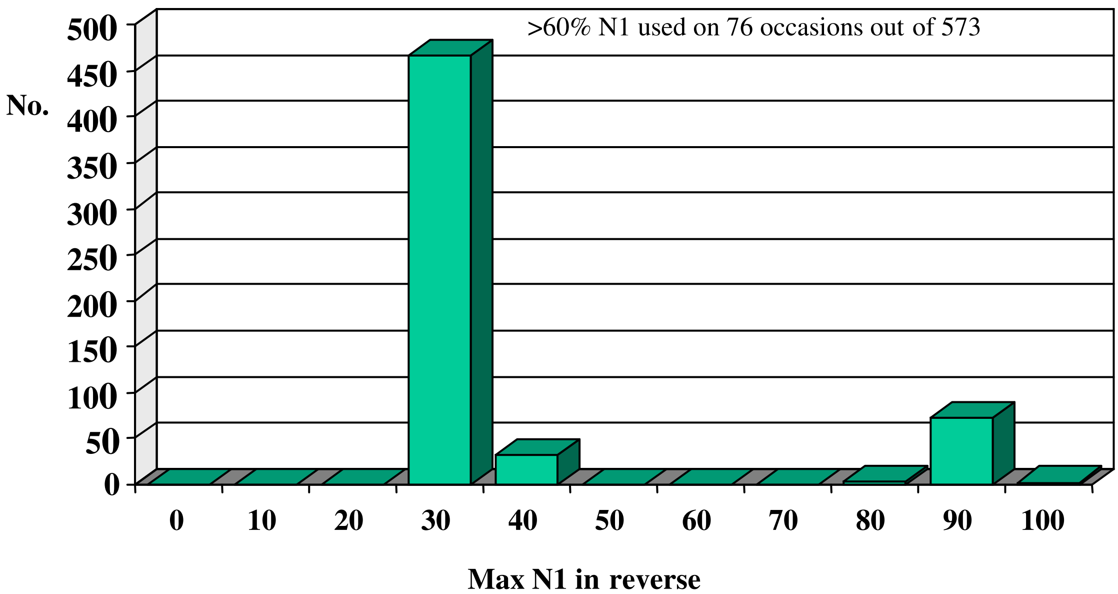


Figure 2. Maximum Reverse Thrust (N1%) use - Boeing 767-336

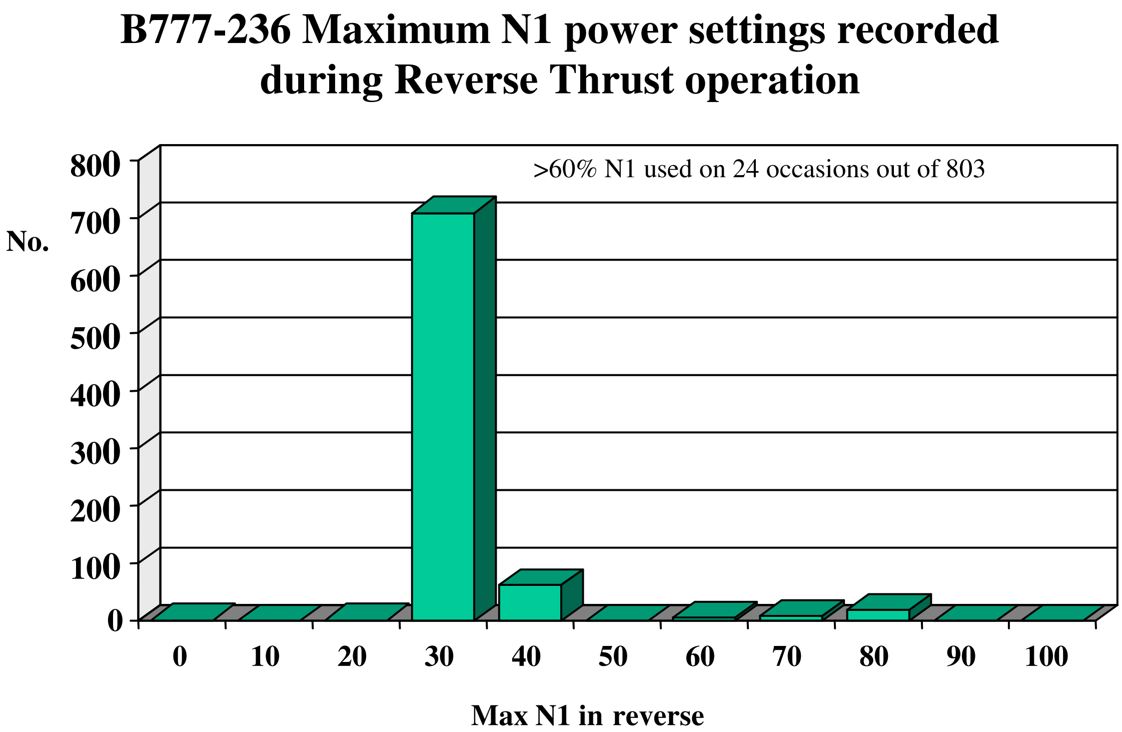


Figure 3. Maximum Reverse Thrust (N1%) use - Boeing 777-236

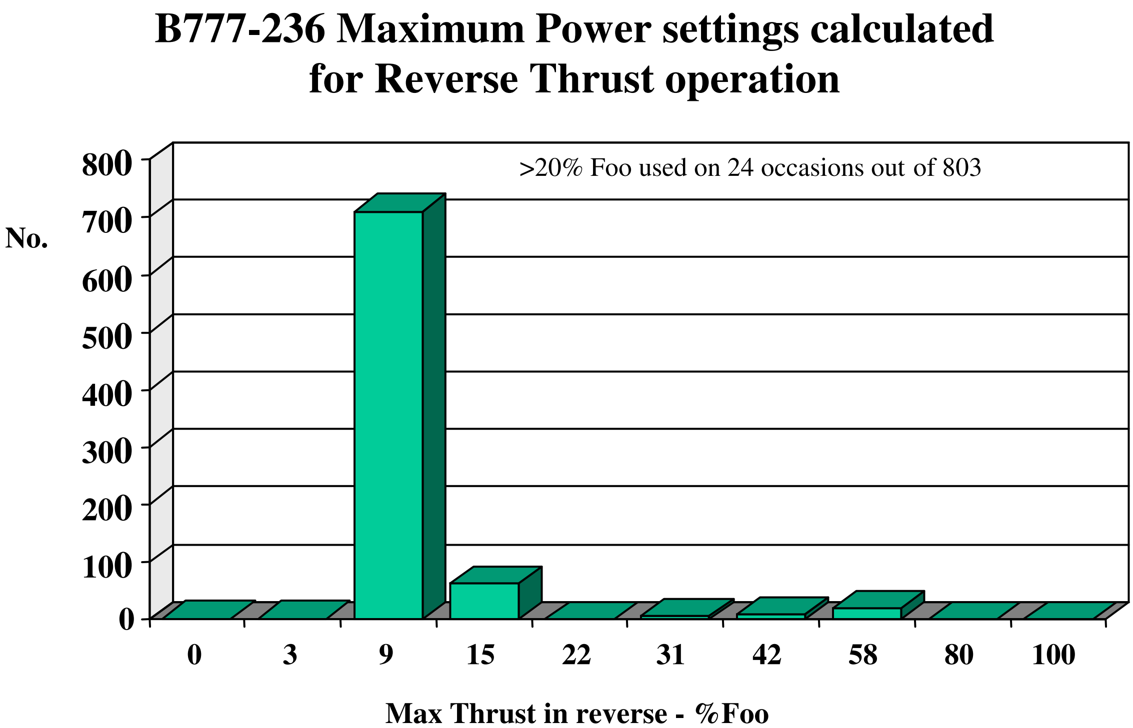


Figure 4. Maximum Reverse Thrust (%Foo) use - Boeing 777-236

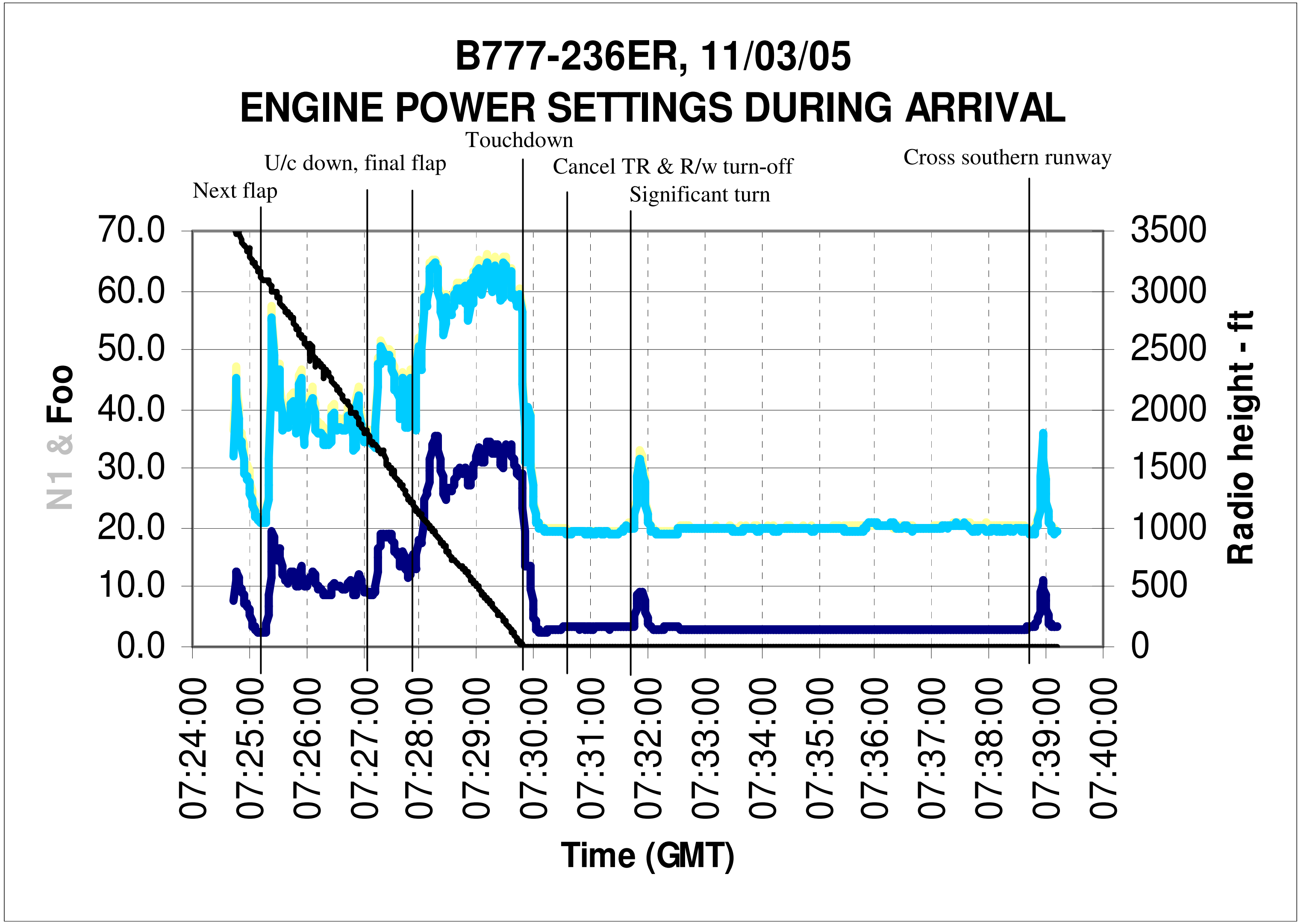


Figure 5. Boeing 777-236 FDR N1 & Power Trace - 1

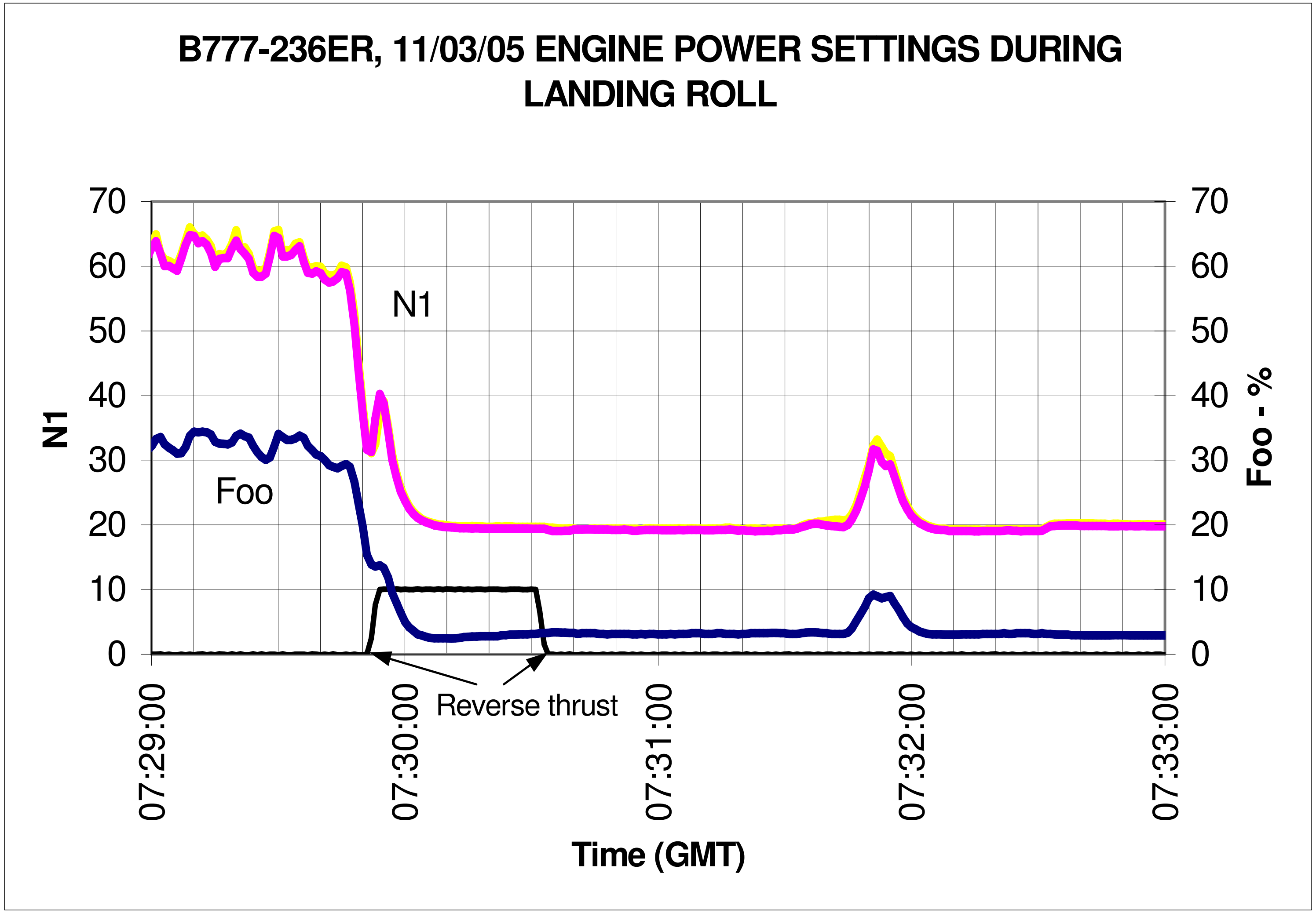


Figure 6. Boeing 777-236 FDR N1 & Power Trace - 2

**BRITISH AIRWAYS**
**ENVIRONMENTAL AFFAIRS**

# Results from a number of surveys of power settings used during taxi operations


## SUMMARY

Although 7% of full rated power is assumed as the idle/taxi power setting for the ICAO certification scheme for aircraft main engine emissions, a number of operational surveys have demonstrated that, in practise, power levels much lower than this actually occur. For most engine types, levels of around 5% to 6%, appear to be the actual power settings used, however for Rolls Royce engines, the levels appear to be even lower at between 3% and 5% of the "Rated Output" thrust level.


## 1. Introduction

In the absence of actual information on actual taxi/idle thrust levels for aircraft engines during normal operations, the ICAO databank figure of 7% is almost universally taken to represent this phase in the calculation of aircraft emissions for local air quality assessments.

This note is intended to provide some actually recorded information for the operations of a number of aircraft types to provide a basis for the estimation of the likely magnitude of error involved when using the ICAO databank levels.

## 2. Analysis

A number of surveys have been carried out to investigate the actual power settings used during taxi operations. These are listed below:

i. Study carried out by Loughborough of British Airways and Caledonian Airways operations at Gatwick airport in 1995 (BROOKE 1995)

ii. Study carried out by British Airways of operations of it's Heathrow based aircraft types at Heathrow, recorded during the LIDAR study measurement campaign by Manchester University in 2005 (unpublished)

iii. Survey carried out by IATA of operational practises of a number of international operators world-wide operations for ICAO Working Group 2, Task Group 4 in 2005 (GERENCER 2005)

iv. Survey carried out by BAA of operational practises of members of the Heathrow airport Flight Operations Committee (FLOP-C), operations at Heathrow airport for PSDH in 2005 (DAWES 2005)

For all studies, operators provided details of recorded taxi fuel flows.

In addition for the first two studies listed a limited analysis of flight data obtained from the quick access flight data recorder (QAR), fitted to British Airways aircraft. For this, a computer programme, called SESMA, originally developed to monitor and capture "events" recorded by the QAR which fell outside "normal" pre-set parameters, was used to record the fuel flows during the taxi in and taxi out phases of the operation at London's Heathrow and Gatwick airports.

An analysis of all the fuel flow data obtained, was carried out to identify the corresponding taxi power setting in terms of the ICAO defined "Rated Output", Foo. For this analysis, the fuel flows recorded were turned into percentages of Foo using the method recommended in CAEP/6 IP/5 (ICAO 2003), which is to use a polynomial fit of the power setting to the recorded fuel flow.

## 3. Results

Results from the analysis are presented in Figure 1 below, for all types – note that there is more than one operator for most types shown, and also some aircraft will contain information for more than one engine type.

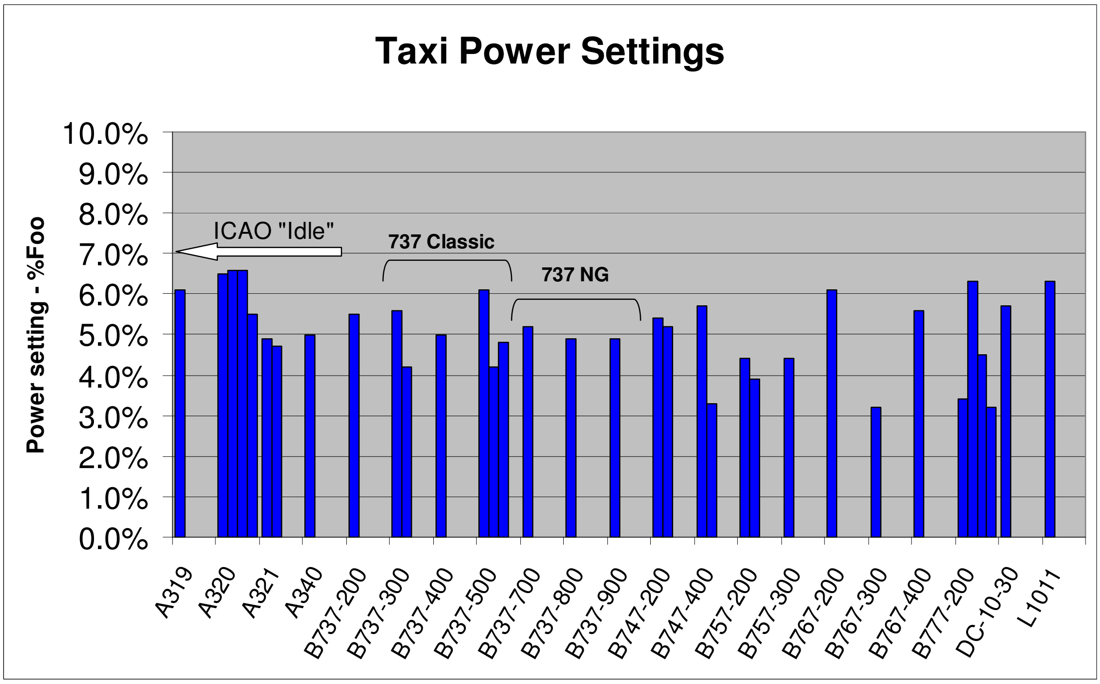


*Figure 1: Recorded power settings for a number of aircraft types.*

### 3.1 Variation with aircraft gross mass

Additional details were available for the British Airways study for a number of types, where the use of the QAR allowed fuel flows to be analysed at a range of aircraft gross masses. The results are shown in figures 2 to 10, and demonstrate that for these operations at least, there was little or no variation in taxi power setting evident with aircraft gross mass. Note that for some types, a higher level of "breakaway" thrust could also be identified and the levels are noted on the chart when recorded.

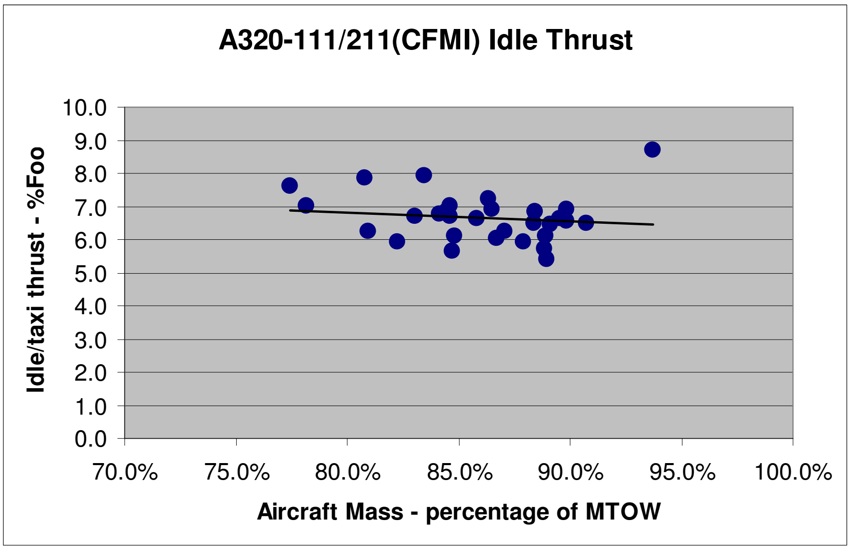


*Figure 2: Recorded power settings vs. mass for A320-100/200 CFM56 engines.*

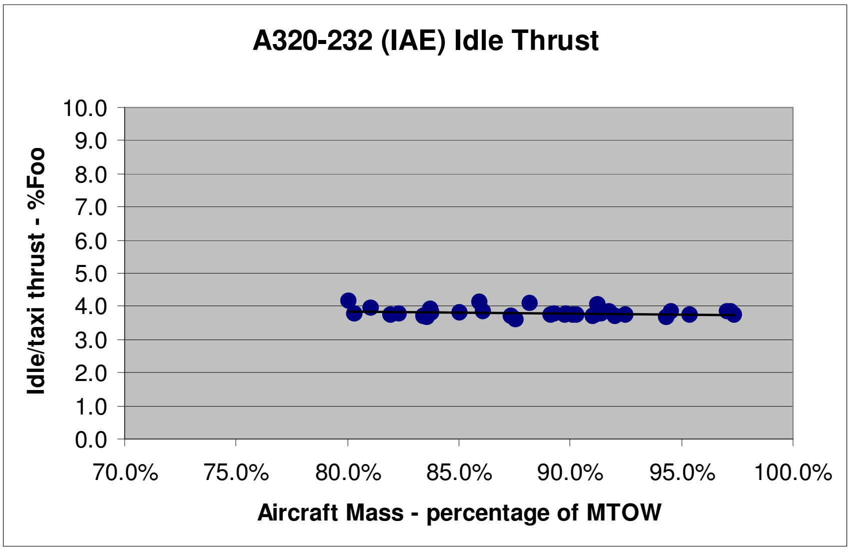


*Figure 3: Recorded power settings vs. mass for A320-100/200 V2500 engines.*

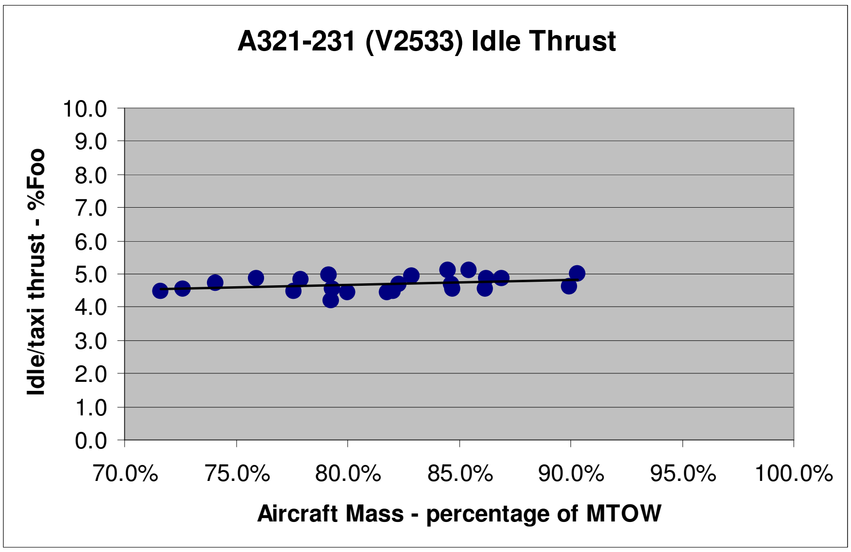


*Figure 4: Recorded power settings vs. mass for A321-200.*

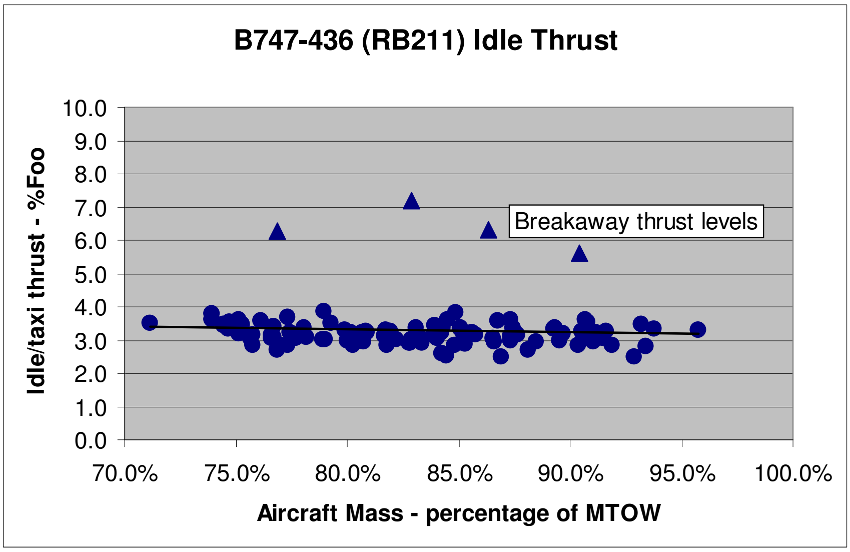


*Figure 5: Recorded power settings vs. mass for B747-400.*

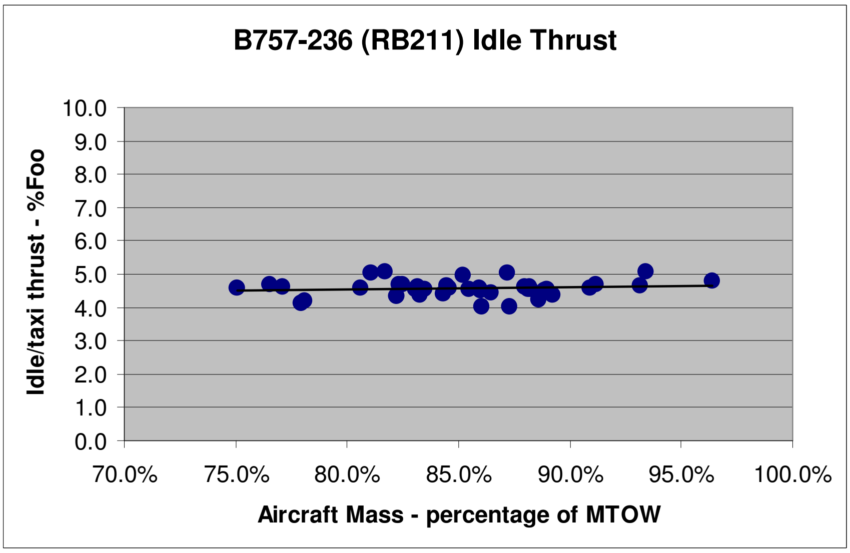


*Figure 6: Recorded power settings vs. mass for B757-200.*

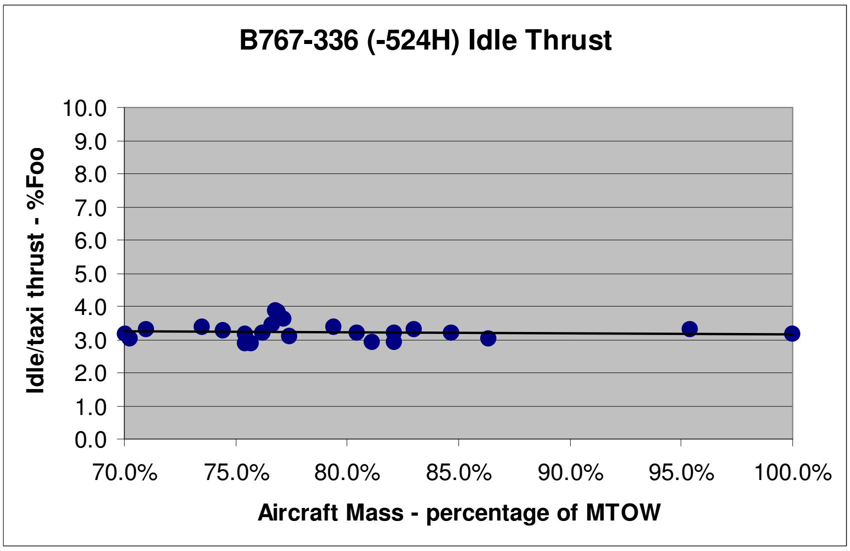


*Figure 7: Recorded power settings vs. mass for B767-300.*

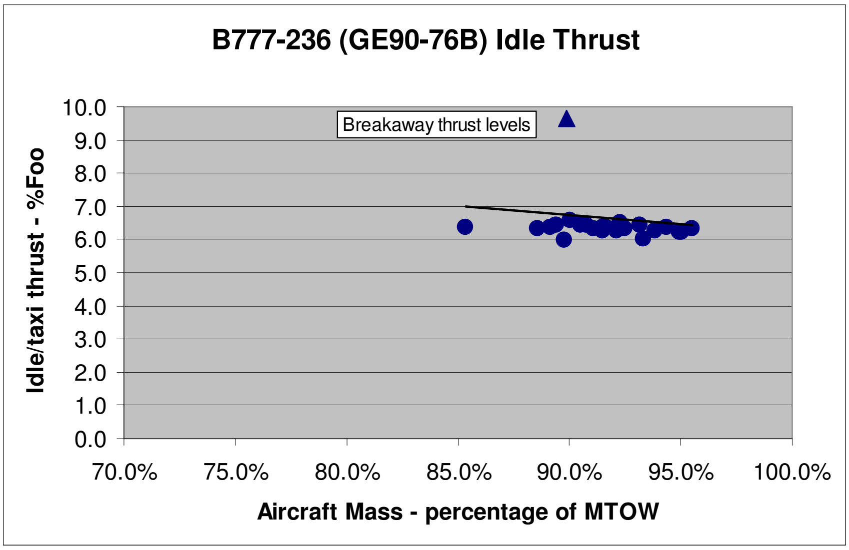


*Figure 8: Recorded power settings vs. mass for B777-200.*

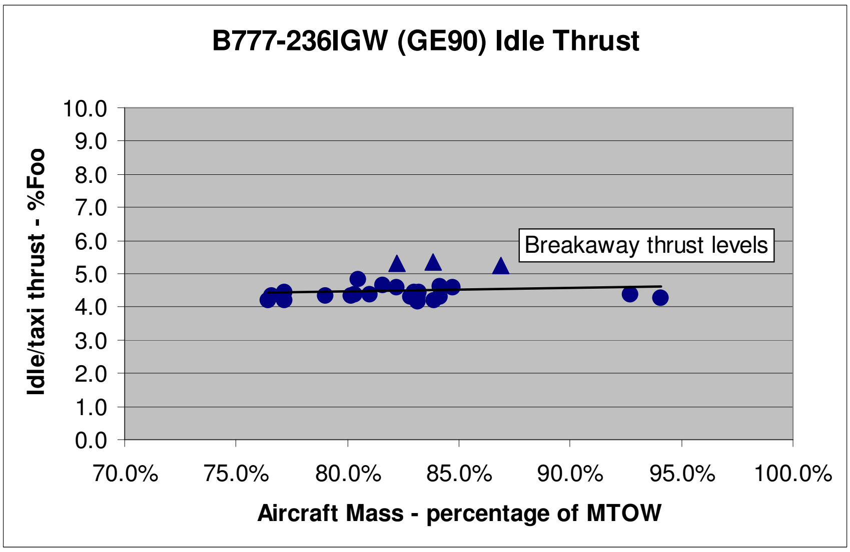


*Figure 9: Recorded power settings vs. mass for B777-200IGW.*

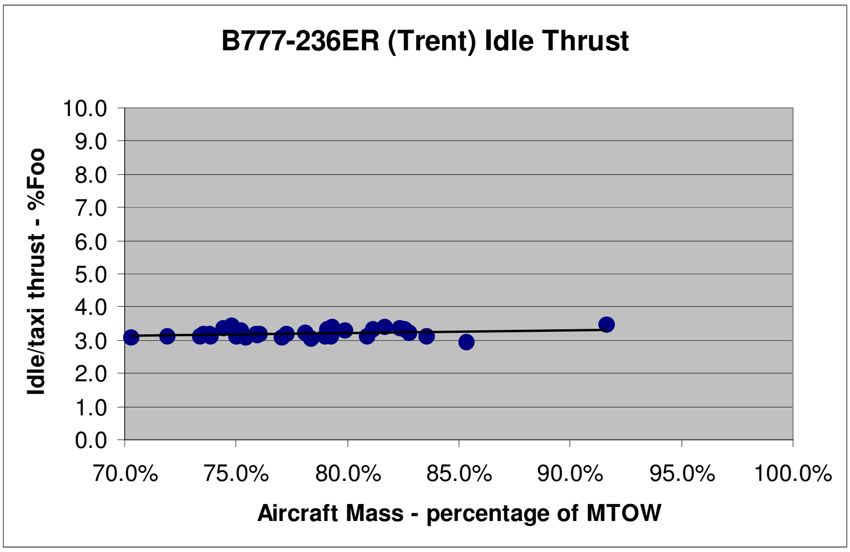


*Figure 10: Recorded power settings vs. mass for B777-200ER].*

3.2 Variation due to taxiing with less than all engines operating

For the IATA survey carried out for ICAO CAEP Working Group 2, one carrier also gave fuel flow details for taxi with one, or two engines shut down. This information showed that it was necessary to increase the remaining, operating engines, to a higher thrust level. The details are show in figure 11, for each type it can be seen that a successively higher power setting is required to taxi with each engine shut down.

For twin engined aircraft, the increase appears to be between 1.5% and 3% of Foo, whereas for the four engined aircraft, shutting down the fist engine only appears to require about 0.5% increase in power setting, however, shutting down the second engine requires another increase of approximately 1% of Foo.

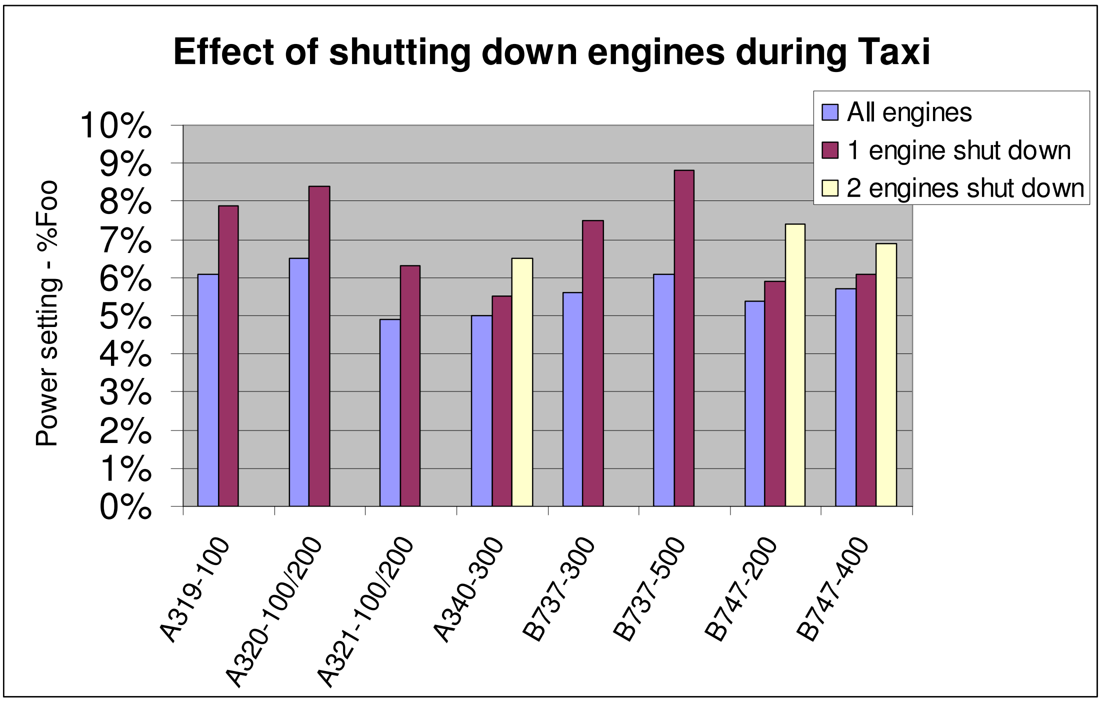


*Figure 11: Recorded power settings for a number of aircraft types with less than all engines operating.]*

## 4. Conclusions

From the results of a number of surveys of actual operational practise, it is apparent that levels of around 5% to 6%, appear to be the actual power settings used for taxiing operations, although for Rolls Royce engines, the levels appear to be even lower at between 3% and 5% of the ICAO “Rated Output” (Foo) thrust level.

As a result, although 7% of full rated power is assumed as the idle/taxi power setting for the ICAO certification scheme for aircraft main engine emissions, a number of operational surveys have demonstrated that, in practise, power levels much lower than this actually occur for most engine types.

A limited study of taxiing with less than all engines operating shows that this has the effect of requiring the live engines to operate at a higher power setting. The results also suggest that when shutting down one engine, the required increase in thrust is much greater for twin engined aircraft than for those with four engines

## 5. References

BROOKE, A.S, CAVES, R.E, JENKINSON, L.R , Methodology for Assessing Fuel Use and Emissions of Aircraft Ground Operations, TT 95 R 05, Loughborough University of Technology, December 1995.

DAWES, Jane, Results from LHR AOC Carrier survey (unpublished data) BAA, September 2005.

GERENCER, Christine, Survey of operational practises that result in improved fuel efficiency and potential emissions reduction benefits–Overview of survey results, WG 2-TG 4-IP, AA/IATA, June 2005.

ICAO, WG3 Rapporteur, Guidance on the use of LTO emissions certification data for the assessment of operational impacts**,** CAEP/6-IP/5, ICAO, November 2003.

Kevin M Morris,
Manager Environmental Affairs,
10th October 2005
ENV/KMM/1126/14.8

**BRITISH AIRWAYS / BAA HEATHROW**
**ENVIRONMENTAL AFFAIRS / AIRSIDE ENVIRONMENT**

# Results from two surveys of the use of Reverse Thrust of aircraft landing at Heathrow airport

## SUMMARY

To gain more information about the use and duration of the use of reverse thrust for both British Airways and other operators for input into modelling of local air quality impacts of aircraft operations, a joint British Airways/BAA survey was carried out at Heathrow airport on October 26th and November 1st 2005, of landing aircraft.

The results suggest that the majority of operators (60%) use no more than idle thrust during the reverse thrust phase, and that the average duration of reverse thrust, on those occasions that it was applied, was approximately 19 seconds.

## 1. Introduction

The use of reverse thrust for British Airways operations at Heathrow airport, has been reasonably well identified through a number of reports and surveys, and has been reported to ICAO CAEP Working Group 2 (MORRIS, 2005). Although some observations were carried out for input into the BA/BAA modelling exercise in 2001 (ARMSTRONG 2001) on runway occupancy after landing, no details of reverse thrust were recorded and it was considered necessary to conduct an additional survey to update the results. This was carried out as a joint study between British Airways and BAA, at Heathrow airport on October 26th and November 1st 2005.

## 2. Analysis

For this survey, the dates chosen were 26th October, and 1st November 2005, the prevailing weather conditions were noted as:

| | 26th October | 1st November |
|---|---|---|
| Wind speed | 7 - 8 kt | 12 kt |
| Wind direction | Southerly | South-westerly |
| Pressure | 1014 mB | 1012 mB |
| Temperature | 17 °C | 12 °C |
| Precipitation | None | None |
| Visibility | 12 - 15 km | CAVOK |
| Runway state | DRY | DRY |

All observations were made during the daytime, between 09:00 and 13:30 local time, so that no special rules regarding the use of reverse thrust at night were in force. Also the runway state remained DRY, with no Low Visibility Procedures (LVP) in place, which again meant that normal procedures were being used, and were not affected by the ambient conditions prevailing at the time.

Observations were made and recorded by hand of landings on runways 27L and 27R at Heathrow airport, as due to the prevailing wind direction, these were the runways in use for the duration of the survey. The time from wheel touchdown (identified by tyre smoke) until turn-off from the runway was recorded, and the time for any thrust reverser operation was also noted. Identification of whether the landing aircraft utilised reverse thrust above the idle power setting was relatively straightforward, as the rise in noise associated with power increase during the reverse thrust operation, was clearly noticeable and obvious.

Two locations were chosen, one for 27L and one for 27R, such that the point of touchdown on the runway to the end of the landing rollout where the aircraft turned off onto the taxiways was visible.

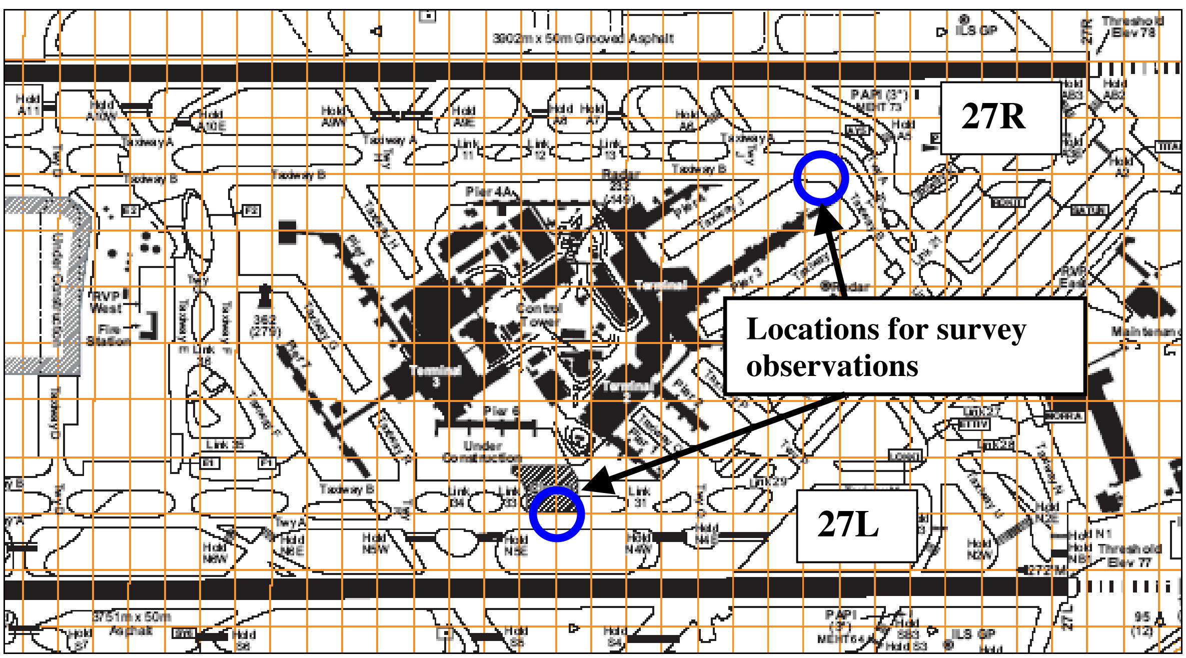


*Figure 2: Arrival runways and observing locations used for Heathrow airport 27L and 27R arrivals.*

A note of the aircraft type was made so that any trend in reverse operation due to different types might be identified, and BAA Heathrow also noted the operator of the aircraft for future analysis.

## 3. Results

The results of the survey are summarised below in Table 1, along with the 2001 data.

| **Aircraft type** | **No. of observations** | **Percentage using greater than reverse idle** | **Average time in reverse greater than idle (sec)** | **Average time for landing roll-out on runway (sec) 2005 survey** | **Average time for landing roll-out on runway (sec) 2001 survey** |
|---|---|---|---|---|---|
| A300 | 0 | -- | -- | -- | 45 |
| A310 | 1 | 100% | 27 | 57 | -- |
| A319 | 33 | 15% | 16 | 32 | 36 |
| A320 | 32 | 59% | 18 | 37 | 36 |
| A321 | 23 | 35% | 21 | 34 | 36 |
| A330 | 3 | 67% | 19 | 46 | -- |
| A340 | 2 | 50% | 32 | 64 | 45 |
| B737 | 15 | 93% | 19 | 40 | 35 |
| B747 "Classics" | 2 | 100% | 33 | 55 | 57 |
| B747-400 | 13 | 23% | 21 | 48 | 49 |
| B757 | 13 | 8% | 2 | 37 | 35 |
| B767 | 8 | 38% | 16 | 38 | 46 |
| B777 | 16 | 31% | 17 | 45 | 54 |
| BAe 146 | 0 | n/a* | n/a* | -- | -- |
| Canadair RJ | 1 | ? | ? | 30 | -- |
| DC10 | 0 | -- | -- | -- | 56 |
| EMB 145 | 1 | 100% | 13 | 27 | -- |
| F70/100 | 1 | 0% | 0 | 36 | -- |
| MD11 | 1 | 100% | 24 | 47 | 44 |
| MD80/90 | 4 | 25% | 16 | 34 | -- |
| Biz jets (e.g., Learjet) | 1 | 100% | 33 | 59 | 37 |
| Props (e.g. F50) | 0 | -- | -- | -- | -- |
| **Airport average** | **170** | **40%** | **19 sec** | **38 sec** | |

*Table 1: Survey results for thrust reverse use and runway occupancy time averages.*

* NB BAe 146 aircraft, and their developments, are not fitted with reverse thrust.

In all 174 recordings were made, though for 4 landings it was impossible to determine whether reverse thrust was used or not, due to the proximity of taxiing aircraft to the observing location. As a consequence, these 4 observations have not been used in the above analysis.

Approximately 40% of aircraft landings observed were identified as using reverse thrust at more than idle power, with the other 60% at reverse idle only. The average time spent with reverse power operating was about 19 seconds, and when used, appeared to be initiated approximately 5 seconds from touchdown. The average duration of the ground rollout for all types was about 38 seconds.

There was quite a variation in both use and duration of reverse thrust used between types, with a few recordings (mainly Boeing 757, and 777 aircraft) using no more than 2 or 3 seconds of reverse power before retarding the throttles to idle. Other aircraft, principally the older Boeing 747's, an A340 and the Gulfstream IV (biz jet), used a significant amount of reverse thrust coupled with a long rollout along the runway to one of the rapid exit turn-offs (RET's) further down the runway.

## 4. Conclusions

A survey was carried out at Heathrow airport on October 26th and November 1st 2005, of landing aircraft, to gain more information about the use and duration of the use of reverse thrust.

The results suggest that only a minority of operators (40%) use more than idle thrust during the reverse thrust phase, and that the average duration of reverse thrust when applied was approximately 19 seconds.

Older Boeing 747's, an A340 and the single military Gulfstream IV, tended to use reverse thrust above idle for the greatest amount of time, travelling further along the runway to one of the further RET's.

Comparing the recorded runway occupancy times with results from a previous survey, in general, showed a reasonable agreement to within the accuracy of the recording methods used.

## 5. References


MORRIS, Kevin M, Reverse Thrust Examples from British Airways Operations, WG 2 Task Group 4 IP5/7, British Airways/IATA, June 2005.

ARMSTRONG, Andrew, BUTTRESS, Jenna C, Runway Data, unpublished data, British Airways, February 2001.



Kevin M Morris, Manager Environmental Affairs, British Airways
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2nd November 2005
ENV/KMM/1128/14.18

**BRITISH AIRWAYS**
**ENVIRONMENTAL AFFAIRS**

# An estimation of the tyre material erosion from measurements of aircraft tyre wear

## SUMMARY

For input to the Project for the Sustainable Development of Heathrow (PSDH) study, tyre wear has been estimated both from manufacturer's information, and from weighing individual aircraft tyres, both new and fully worn. Dividing through by the average number of landings between tyre changes suggested values for the average amount of tyre material lost for each landing, for the majority of aircraft types operating at Heathrow. These values are listed below.

| Data source | Aircraft type | Amount lost per landing (kg/landing) |
|---|---|---|
| BA | A319/A320 | 0.078 |
| | A321-200 | 0.107 |
| | B737 Classic | 0.129 |
| | B747-400 | 0.812 |
| | B757-200 | 0.138 |
| | B767-300 | 0.269 |
| | B777-200 | 0.427 |
| Dunlop/FLS | A320 | 0.230 |
| | B737 Classic | 0.178 |
| | B737 NG | 0.329 |
| KLM | F100/BAe 146 | 0.058 |
| Michelin | A320 | 0.154 |


## 1. Introduction

As well as originating from the combustion of fuel in the main engines and APU, one of the main sources of primary $PM_{10}$ emissions from aircraft is considered to be from tyre erosion and brake wear. In this respect, $PM_{10}$ emissions from tyres are likely to be dependent on many factors including aircraft weight, number of wheels, brake material (carbon or steel) weather conditions, engine type, airport runway length and taxiway layout, and operating procedures. However combinations of these dependencies are largely unknown and a more straightforward approach was required in order to predict these emissions for the Heathrow aircraft fleet.

Some limited data was available from measurements made by KLM UK ltd. On a Fokker 100, and BAe 146, however, there was no information available on larger types, and the process to scale these results up to larger aircraft was not considered robust enough without further measurements.

More recently, data had also become available from both Michelin and Dunlop/FLS for aircraft of A320/B737 size, at the request of British Airways, but information on types larger than this was sill not available. As a result, it was decided to carry out some weight measurements of tyres from British Airways aircraft to fill these gaps.

## 2. Analysis

As well as gathering information from the tyre manufacturers, for this analysis, aircraft tyres were individually weighed at the Honeywell facility in Feltham, in January 2006.

A number of new, worn and part worn, tyres were made available by Honeywell, in advance of them being taken either back to the manufacturer for re-treading, or to be refitted to the aircraft wheels for later fitment to aircraft at Heathrow airport.

In all 74 tyres were weighed: 1 part worn, 45 worn, and 28 newly manufactured, using a set of scales normally employed for weighing passengers. This set of scales were chosen, as they covered the range of expected tyre weights (up to about 150 kg), and gave the accuracy required (0.1 kg) for this exercise.

The distributions of tyres weighed, and average weights, are shown in table 1, below:

| Aircraft | Tyre position | Number weighed **New** | | Number weighed **Worn** | |
|---|---|---|---|---|---|
| | | No. weighed | Average wt. Kg | No. weighed | Average wt. Kg |
| A319/320/321 | Nose-wheel | 4 | 21.1 | 3 | 19.5 |
| A319/320 | Main-wheel | 4 | 75.9 | 6 (1 part worn) | 68.3 |
| A321 | Main-wheel | - | - | 1 | 85.1 |
| B747 | Nose/main-wheel | 6 | 122.6 | 18 | 114.4 |
| B767 | Nose-wheel<br>Main-wheel | 5<br>5 | 53.0<br>115.9 | 2<br>4 | 48.4<br>107.2 |
| B777 | Nose-wheel<br>Main-wheel | -<br>4 | -<br>99.8 | 5<br>6 | 56.0<br>90.7 |
| **Total** | | **28** | | **46** | |

*Table 1: Summary of tyre weighing carried out in Feltham.*

The part worn tyre had been removed as the result of a deep cut in the crown of the tyre, found as part of the tyre inspection process before every flight and during routine maintenance. As a result, although it was weighed, it's weight was not used in the survey as it was considerably heavier than other full worn tyres and was not considered to be representative for this exercise.

## 3. Results

The average weight loss was then calculated from the unused – fully used tyre weights. Where data existed for re-treaded tyres this was also factored into the results, and if data was absent from one source, then data from another source was combined to obtain the results.

All the measured data resulting from this exercise (manufacturer's measurements and the British Airways survey) has been combined and is shown in Table 2, along with information for the average number of landings between tyre changes.

| A/C | | NEW UNUSED | NEW USED | RUBBER WORN kg | RETREAD UNUSED | RETREAD USED | RUBBER WORN kg | AVERAGE LOSS - kg | LANDINGS /TREAD | WEIGHT LOSS/ LDG - kg | PER A/C LANDING | TOTAL PER A/C LDG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B737 | MAIN | 70.4kg | 63.7kg | 6.7 | 71.6kg | 64.1kg | 7.5 | 7.39 | 280 | 0.0264 | 0.10551 | |
| | | | | | | | | | | | | 0.129 |
| B737 | NOSE | 17.4kg | 15.8kg | 1.6 | 18.1kg | 16.0kg | 2.1 | 2.03 | 170 | 0.0119 | 0.023866 | |
| | | | | | | | | | | | | |
| B757 | MAIN | 70.4kg | 63.7kg | 6.7 | 71.6kg | 64.1kg | 7.5 | 7.39 | 500 | 0.0148 | 0.118171 | |
| | | | | | | | | | | | | 0.138 |
| B757 | NOSE | 33.1kg | 29.8kg | 3.3 | 33.6kg | 31.2kg | 2.4 | 2.53 | 250 | 0.0101 | 0.020229 | |
| | | | | | | | | | | | | |
| A319/320 | MAIN | 75.9kg* | 68.3kg* | 7.6* | | | 7.6* | 9.222 | 530 | 0.0174 | 0.0696 | |
| | | | | | | | | | | | | 0.077 |
| Airbus | NOSE | 21.1kg* | 19.5kg* | 1.6* | | | 1.6* | 1.4129 | 398 | 0.00355 | 0.0071 | |
| | | | | | | | | | | | | 0.107 |
| A321 | MAIN | 86.1kg | 85.1kg* | | | | | 10 | 400 | 0.0250 | 0.1 | |
| | | | | | | | | | | | | |
| B747 | MAIN | 122.6kg* | 114.4kg* | 8.1* | | | 8.122* | 8.122 | 180 | 0.0451 | 0.8122 | 0.812 |
| | | | | | | | | | | | | |
| B767 | MAIN | 115.9kg* | 107.2kg* | 8.7* | | | 8.705* | 8.705 | 300 | 0.0290 | 0.232133 | |
| | | | | | | | | | | | | 0.269 |
| B767 | NOSE | 53.0kg* | 48.4kg* | 4.6* | | | 4.58* | 4.58 | 250 | 0.0183 | 0.03664 | |
| | | | | | | | | | | | | |
| B777 | MAIN | 99.8kg* | 90.7kg* | 9.2* | | | 9.2* | 9.92 | 310 | 0.0320 | 0.384 | |
| | | | | | | | | | | | | 0.427 |
| B777 | NOSE | 62.6kg | 56.0kg* | | | | | 6.6096 | 306 | 0.0216 | 0.0432 | |
| | | | | | | | | | | | | |

*** data from tyre survey weighing on 24th January 2006.***

*Table 2: Summary of tyre wear results from all sources.*

For the PSDH study, a methodology was required to extend the results of tyre erosion to other types not measured. As the data from this exercise now contains a significantly larger range of aircraft types over an extended range of sizes, this has been used to estimate the rates for other aircraft by normalising by aircraft maximum take-off weight (MTOW). The results from this are given in table 3 below.

| Data source | Aircraft type | Amount lost per landing (kg/landing) | MTOW (kg) | Normalised amount lost per landing (kg/kg max take-off weight/landing) x $10^{-6}$ |
|---|---|---|---|---|
| KLM | F100/BAe146 | 0.058 | 43090[1]/44225[2] | 1.35/1.31 |
| BA | A319-100 | 0.078 | 64000[3] | 1.22 |
| Dunlop/FLS | A320 | 0.230 | 73500[4] | 3.13 |
| Michelin | A320 | 0.154 | 73500[4] | 2.10 |
| BA | A320-100/200 | 0.078 | 68000/73500[3] | 1.15/1.06 |
| BA | A321 | 0.107 | 89000[3] | 1.202 |
| Dunlop/FLS | B737 Classic | 0.178 | 57833/62820/53886[4] | 3.08/2.83/3.30 |
| BA | B737 Classic | 0.129 | 57833/62820/53886[3] | 2.23/2.05/2.39 |
| Dunlop/FLS | B737 NG | 0.329 | 70080[5] | 4.69 |
| BA | B747-400 | 0.812 | 381000/396890[3] | 2.18/2.05 |
| BA | B757-200 | 0.138 | 99700[3] | 1.38 |
| BA | B767-300 | 0.269 | 158000/181400[3] | 1.70/1.48 |
| BA | B777-200 | 0.427 | 242670/267619/297556[3] | 1.76/1.60/1.44 |

Data References:

1 – Fokker 100 Technical Description, Fokker B.V. June 1986.
2 – BA Connect, BAe 146-300.
3 – BA Weight and Balance Manual for the specific type.
4 – Boeing 737-300/-400/-500, assumed same as for BA aircraft.
5 – Boeing 737-700 MTOW from Boeing website.

*Table 3: Consolidation of all tyre wear results with aircraft MTOW.*

To show the variation with MTOW, and any differences in the measured results from the different sources, these have been plotted against MTOW, and are graphically illustrated below in Figures 1 and 2.

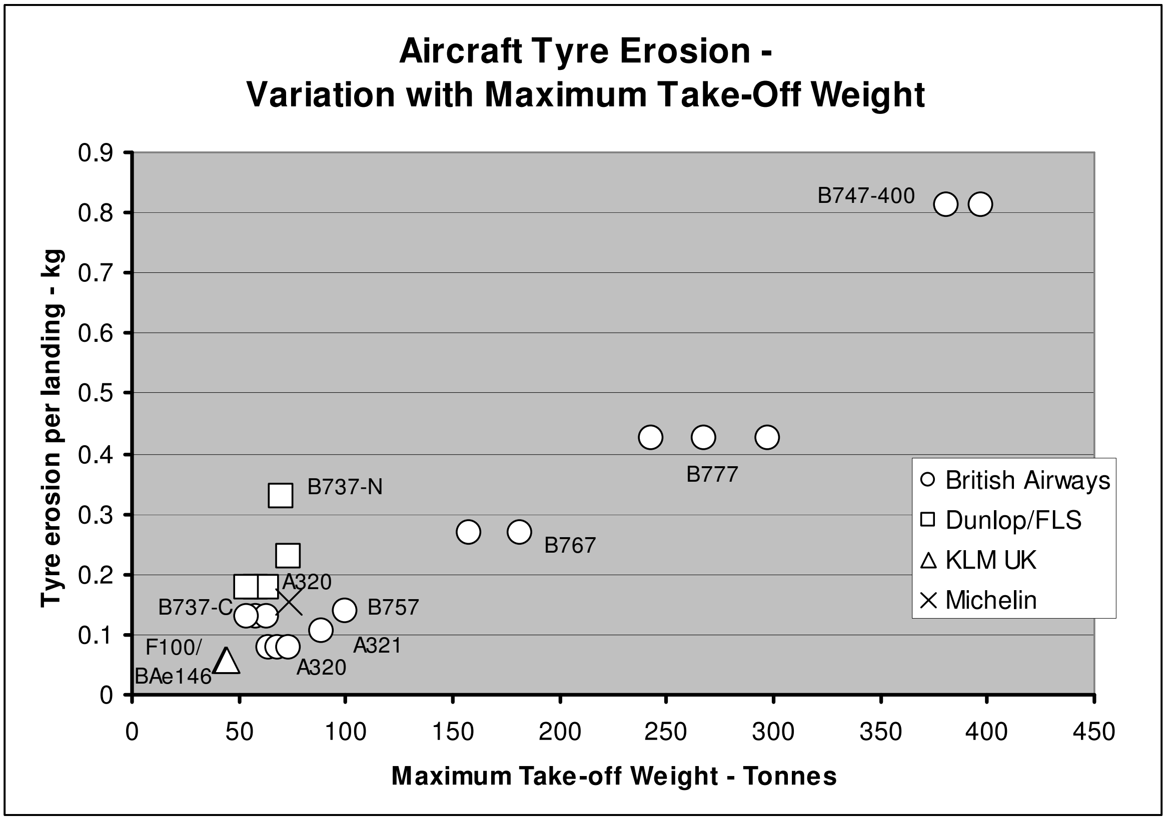



Figure 1: Aircraft tyre wear results with aircraft MTOW.

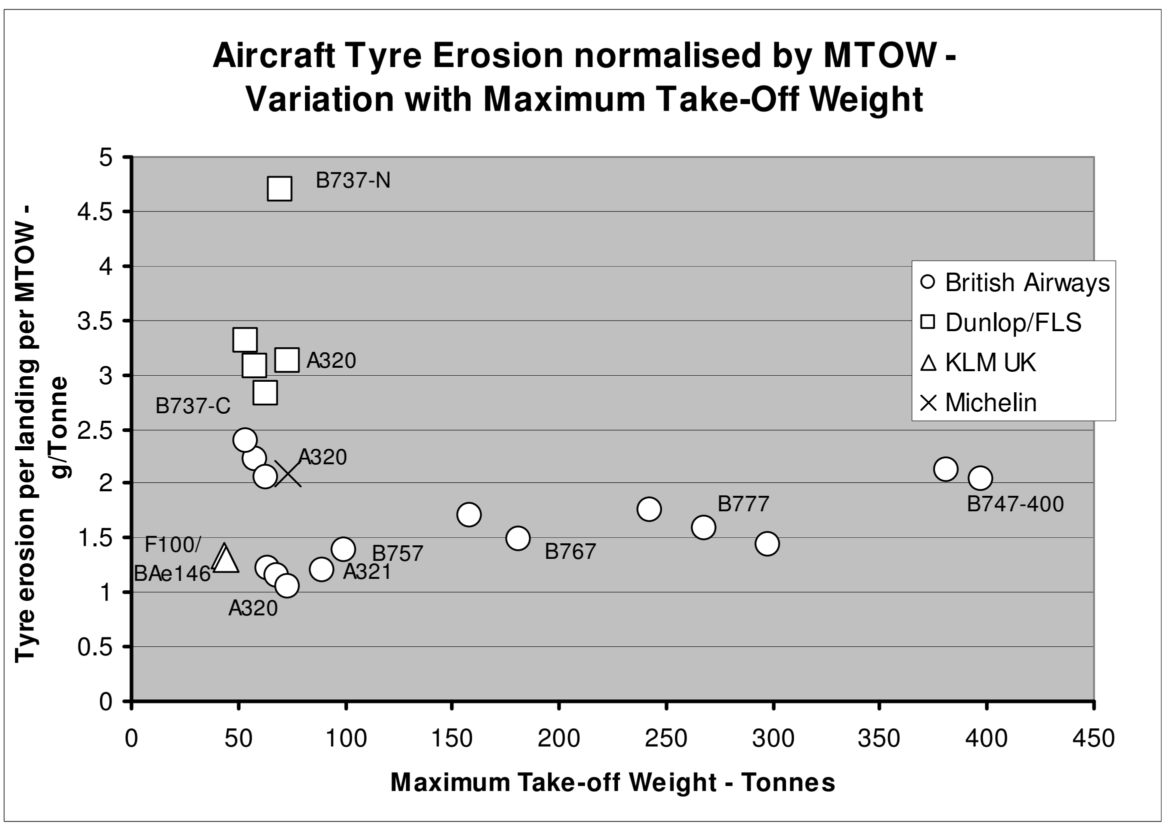



Figure 2: Aircraft tyre wear results normalised by MTOW, with aircraft MTOW.

## 4. Conclusions

The results from additional measurements of tyre rubber loss weights carried out at Honeywell in Feltham, have considerably added to, and extended the range of information on tyre wear for aircraft tyres over that which had previously existed.

The results from the BA study appear to suggest a relatively simple relationship with aircraft MTOW, and are reasonably consistent with other studies carried out on smaller aircraft types, especially the KLM UK results. There is, however, considerable variation at the lower MTOW, between this and other surveys for the A320, with the Dunlop/FLS measurements up to 3 times greater, and the Michelin data about midway between the two. Without knowledge of the number of landings assumed for these surveys, however, it is difficult to make any further judgements.

The results of these surveys have been passed to Qinetiq, who will continue with the construction of a methodology for PSDH.

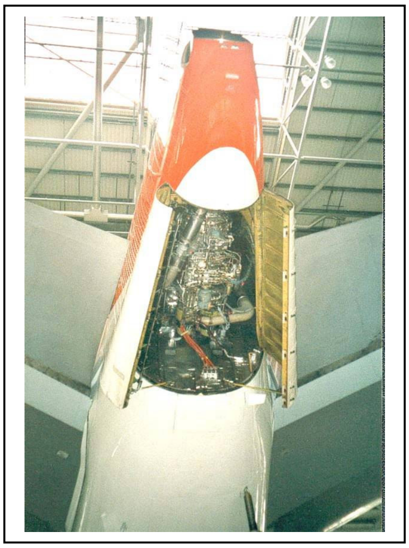
Kevin M Morris, Manager Environmental Affairs,
3rd April 2006
ENV/KMM/1131/14.18

**BRITISH AIRWAYS**
**ENVIRONMENTAL AFFAIRS**

Analysis of APU emissions characteristics to provide a methodology for use in emissions inventories at Heathrow airport

## 1. Introduction

The Auxiliary Power Unit (APU) is a small gas-turbine engine coupled to an electrical generator, and is used to provide electrical and pneumatic power to aircraft systems when required. It is normally mounted in the tail cone of the aircraft outside behind the rear pressure bulkhead, and runs on kerosene fed from the main fuel tanks. Not all aircraft are fitted with APU's, and though their use on transport category jet aircraft is now almost universal, turboprops, and some Biz-jets do not have an APU fitted.



Although it is not normally a requirement to have an operable APU for most operations, it is mandatory for EROPS flights, and can be used as a backup system for dispatch, for example, when one main engine driven generator is unserviceable.

APU's are not certificated for emissions, unlike aircraft main engines, and information on APU emissions rates are generally not publicly available. Generalised emissions have been made public in a letter from Honeywell to the US EPA (Honeywell 2000), for use in their EDMS emissions modelling system. This information has been used in the past to construct airport emissions inventories, which have given rise to values of APU emissions, of NOx, of between 9% and 18% of all ground level emissions from aircraft. Given these results, which are not insignificant, and the level of uncertainty associated with them it has been important to attempt a more accurate assessment of APU emissions, and to extend this to particulate emissions (particularly PM10) where possible.

Recent information from Honeywell to British Airways (Honeywell 2006), gives significantly more detail to this earlier letter, and also includes emissions indices for PM10 emissions, however, due to reasons of confidentiality to the manufacturer and US legal requirements under the Export Administration Regulations (EAR), this information cannot be made public.

This paper provides the methods used in an analysis of the Honeywell APU data, and similar information obtained from Pratt & Whitney Canada, for the PW901A APU, (PWC 1998) so that a more accurate assessment of APU emissions at airports could be made for PSDH.

## 2. Analysis and Results

The analysis of APU emissions characteristics was carried out in four parts: NOx emissions, PM10 emissions, assignment of APU groups to aircraft types, and the relevant load cycles or times-in-mode.

The analysis of each of these along with recommended characteristic NOx and PM10 production rates and default times-in-mode, are described individually in each section, below.

### 2.1 Emissions characteristics – NOx

NOx emissions indices were converted into production rates, by multiplying through by the fuel flow for each APU type, and operating condition. For this a simplifying assumption was made that all APU's operate at an intermediate mode of "Maximum ECS" only, as the fuel flows and emissions characteristics appear not to vary significantly with load off-take for the main part of their operating cycle. In this way, only three modes were required to be analysed which simplifies the process of emissions estimation from APU's without loosing too much accuracy.

In addition, as "Max ECS" was the condition where the APU operates longest, and hence is the part of the cycle where most NOx was produced, the grouping of APU's into one of five characteristic types focusing on this mode was the priority.

From this analysis, a characteristic, average, NOx production rate for each APU group was derived.

### 2.2 Emissions characteristics – PM10

Particulate emissions were originally supplied in terms of the SAE Smoke-Number parameter (i.e. SN), and the PWC901A engine, and some Honeywell types did not have corresponding PM10 index information to go with the Smoke Number. As a result these had to be estimated from the data available from other types of APU.

All parameters were plotted to find the best way of characterising the relationship between the reported SN and EI PM10, and it was found that the best fit was between SN and PM10 production rate.

The second part of the analysis was to identify a relationship that would allow PM10 emissions from APU's to be calculated. One constraint for this part was that the PM10 emissions had to be able to be calculated from a parameter that was already publicly available, so the analysis focussed on the relationship between NOx and PM10.

By plotting the PM10 emissions rate against the NOx emissions rate, for all APU's at each operating load, it became clear that they fell conveniently into one of three distinct groups.

From knowledge of the NOx emissions rate identified from section 2.1 above, the PM10 production rate can then be identified for any APU and operating mode.

## 2.3 Aircraft assignment

APU NOx and PM10 class assignments for common current aircraft types were then identified for the PSDH process. A further analysis suggested the best of these classes to be used for aircraft not specifically identified and for future aircraft developments.

## 2.4 Times in Mode (Load cycles)

Discussions with Boeing (Daggett 2002), suggest that the APU takes about 3 minutes from initial start to stabilise before any load is drawn off. For this case the APU is essentially operating in the “no-load” condition.

The end of the operating cycle usually follows the Main Engine Start (MES), when the APU is normally no longer necessary – electrical load and ESC requirements being satisfied by main engine driven generators and air bleeds. The MES portion is, however, the point at which the maximum load is drawn off the APU, and so it is important to identify the times of operation.

Unfortunately no records of APU load cycles have become available, as the aircraft’s Flight Data Recording system doesn’t start recording until main engine start when the APU is shut down. To gain an estimate of this part of the PAU load cycle, a number of management pilots were approached and asked about the timings of the use of APU for main engine start. Their replies were generally in agreement with each other, and gave estimates of 30 seconds for the smaller aircraft (e.g. A319/320/321/B737), about 40 seconds for the larger twins (e.g. B757/B767.B777), and 140 seconds for the Boeing 747 aircraft.

The reason given for the much longer operating time for the Boeing 747 was that the standard procedure for most aircraft was to start one engine and then cross-bleed air from this to start the other(s). For the Boeing 747, APU bleed air is normally used to start each engine in turn, and so the total time was 4 engines x 35 seconds each = 140 seconds. This was also the procedure for starting the engines of Concorde aircraft, however, as Concorde was not fitted with an APU, specialist air-start vehicles were required to perform this function.

The remaining portion of the APU cycle is at an intermediate load supplying air for Environmental Control Systems (ECS) and/or electric power for aircraft systems, as required. It is difficult to be more precise regarding the actual load setting, and time in this condition, as this will vary based on a large number of factors. However, a simplifying assumption has been made that all APU’s operate at maximum ECS only, as the fuel flows and emissions characteristics appear not to vary significantly with load off-take close to this reference point.

The assumption of maximum ECS is justified as conservative at airports where fixed electrical ground power (FEGP) is available (as at Heathrow), as this would provide for the electrical load requirements of the aircraft, leaving the APU to provide bleed air for the ECS. At airports where pre-conditioned air (PCA) is supplied, the APU would only normally be required to start main engines and to supplement the gate facilities, when required.

## 3. Recommendations and Conclusions

The analysis of APU NOx and PM10 emissions data has enabled a useful method for estimating APU emissions of NOx and PM10 to be identified that is more accurate than previous methods, but at the same time still complies with the legal requirements of the Export Administration Regulations.

In the absence of more accurate information, NOx and PM10 emissions can be calculated at three suggested APU operating load conditions of: Start-up (No load), Normal running (Max ECS), and High load (Main Engine Start), to represent the operating cycle of these engines. For each mode, the emissions can be calculated from:

i) NOx = NOx rate x times in mode, and

ii) PM10 = PM10 rate x times in load

Where data for actual times in mode cannot be identified accurately, it is recommended that the appropriate times are used from section 2.4 of this note. These are reproduced in the table below, for convenience.

| Activity | Mode | Two engines aircraft | Four engines aircraft |
|---|---|---|---|
| APU start-up and stabilisation | Start -up | 3 minutes | 3 minutes |
| Aircraft preparation, crew and passenger boarding | Normal running | (Total pre-departure running time) – 3.6 min | (Total pre-departure running time) – 5.3 min |
| Main Engine Start | High Load | 35 seconds | 140 seconds |
| Passenger disembarkation and aircraft shutdown | Normal running | 15 minutes | 15 minutes |

*Table 1: Suggested APU times in mode for a "standard" turnaround cycle.*

The total APU emissions of NOx and PM10, for each turnaround cycle, can then be calculated from a summation of the emissions for each mode over the whole cycle.

## 4. References

Daggett D,2002 APU Emissions Calculation Methodology – letter to Kevin Morris, British Airways, February 2002

Honeywell, 2000, APU emissions – letter from Randall Williams to Bryan Manning, US EPA, September 2000.

Honeywell, 2006, Honeywell APU Emissions for British Airways – Confidential letter to Kevin Morris, British Airways, February 2006.

Pratt & Whitney Canada 1998, Confidential faxed letter from Nick Ngoly, PWC, to Jim Quinn, British Airways, August 1998.

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