DETERMINANTS OF EMISSION FROM GROUND OPERATIONS OF AIRCRAFT

Robert Caves*, Lloyd Jenkinson* and Andrew Brooke**
Department of Aeronautical and Automotive Engineering and Transport Studies,
Loughborough University,
Loughborough, Leics., LE11 3TU, UK.
and Manchester Airport Plc,
Manchester, M22 5PA, UK.

Abstract

The present method of assessing fuel use and the production of emissions by the ground operations of aircraft relies on calculations based in the Standard Landing and Takeoff (LTO) cycle developed by the International Civil Aviation Organisation (ICAO).

This study examined ground operations at Gatwick (London) airport in detail to determine the factors controlling the use of aircraft engines. Over 2000 taxi records were made of traces on the Ground Movement Radar to determine taxi routes, times and characteristics. A 10 per cent sample of these movements provided data on the use of engines from the Flight Data Records of the British Airways fleet.

It was found that the engine power settings were lower than presumed in the ICAO LTO cycle. Fuel flow and emissions were found to be dependent on the time for which the engines were running. This depended primarily on taxi distance, but also on airline policy on engine-out taxiing, on aircraft weight, on familiarity with the airport and on the aircraft movements per hour. More work is needed to calibrate emissions during start-up and at low engine settings, but it can be concluded that the normal methods of estimating emissions will tend to overestimate all emissions except Oxides of Nitrogen.

Introduction

Many studies have been done of aircraft ground operations, but they have usually been focussed on reducing congestion, noise or fuel use. Towing (1), powered landing gear (2), engine-out taxi procedures (3) and fixed ground power (4), are among the ideas which have been considered for reducing these effects. Usually, quite simple assumptions are made about the taxi times and engine settings used when determining the benefits for these ideas, unless an airline undertakes a monitored demonstration project.

It is often argued that it is not necessary to carry out similar studies into the gaseous emissions produced by the ground phase of aircraft operations, since these emissions at airports are largely dominated by road traffic (5), that engines are much cleaner than when the International Civil Aviation Organisation's (ICAO) guidelines were set up, that taxi times have fallen due to holding on stand, and that the focus of attention for aviation emissions has shifted to high altitude. Those studies that have been done have used the rather simple assumptions embodied in the ICAO Landing and Take-Off cycle (LTO) to estimate the production of emissions, though some airports have carried out air quality monitoring and often found it difficult to detect the effect of aircraft operations (6). The LTO cycle assumes 7 minutes for taxi-in and 19 minutes for taxi-out, all at an idle engine setting giving 7 per cent of maximum thrust (F_{max}).

Despite the general validity of these views, it was felt that important aspects of emission production and fuel use were still not understood, and that, as road vehicle engines become cleaner, airside movement rates increase, average aircraft size increases and environmental impacts are being felt in terms of capping of airport capacity, it was necessary to gain a deeper understanding of the controlling factors. Only then would it be possible to evaluate properly any policies to change control

---

* Senior Lecturer
** Facilities Planner, Manchester Airport Plc

procedures, operational practices or airport layout in order to mitigate the production of emissions. For example, introducing straighter taxiway routings would be beneficial if it were shown that power was added to negotiate turns. Also, the central location of the new terminal at Atlanta saved 5 or 6 minutes of taxi time because it eliminated the need to queue to cross active runways: this type of layout modification would have an additional effect on fuel use and emissions if continual stopping and starting were shown to influence them.

A further reason for undertaking the study was the recognition that many things have changed since the LTO cycle was defined, including taxi engine settings, taxi times and engine characteristics. The study should throw light on the possible need to re-define the LTO cycle.

The study therefore investigates the operating procedures of a range of aircraft to determine the factors which control the use of fuel and the production of emissions. The results are intended to help with policy-making with respect to operational practices and the need to redefine the ground part of the LTO cycle.

Methodology

The study comprised five main sections.

Data on some 2500 aircraft ground movements at Gatwick were collected, the time and track information being recorded by video from the ground movement radar display (GMR). Data on engine settings were obtained from Flight Data Recordings (FDR) readouts for a sample of British Airways movements.

Data on engine settings per unit of time were converted into fuel use and emissions production with the use of the ICAO engine database (7).

The fuel and emissions output was related to the characteristics of the engines, the aircraft and the way the aircraft taxied, the latter being derived from the video recordings.

Models were built of the relationships between fuel flow and the factors controlling it, using multiple regression. Similarly, other models were generated for the various emissions.

The models were applied to the complete set of movements by jet aircraft at Gatwick over a year. The gross outputs of fuel use and each pollutant were compared with estimates which would have resulted from the application of the standard LTO cycle.

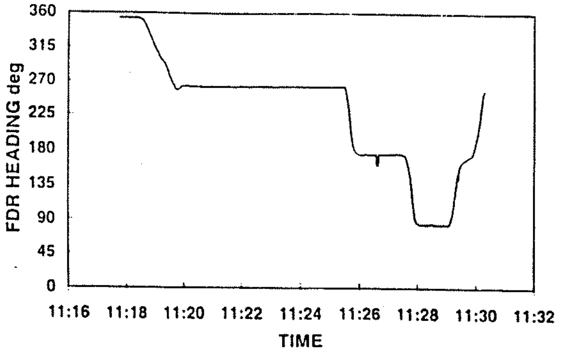
Data Collection

Data collection of aircraft ground movement was conducted at Gatwick Airport over the period of a year from March 1994 to February 1995 by permission of the British Airports Authority (BAA plc). The selection of Gatwick Airport as the case study airport allowed for a large spread of traffic levels and aircraft types available for observation (182,000 air transport movements (atms) in 94-95), including a substantial British Airways (BA) operation. A total of twelve collection visits were made, at a rate of approximately one per month, with an attempt made to encompass variations in time of day, week, season and meteorological conditions. Each session lasted approximately six hours, providing some 200 observations of aircraft ground movement per visit. A total of 2,500 aircraft ground movement observations were collected over the year.

Data was collected from various sources. These included video recording of a slave Ground Movement Radar in the New Control Tower (NCT) at Gatwick Airport (courtesy of National Air Traffic Services, NATS), RT (radio transmission) audio recording and visual observations of all aircraft ground movement. Subsequently, meteorological conditions at the time of the visit were collected from the Meteorological Office, British Airways supplied FDR information for some of the observed ground movements and BAA also supplied arrivals and departures information from their Apron Control System of all movements on the date of the visit.

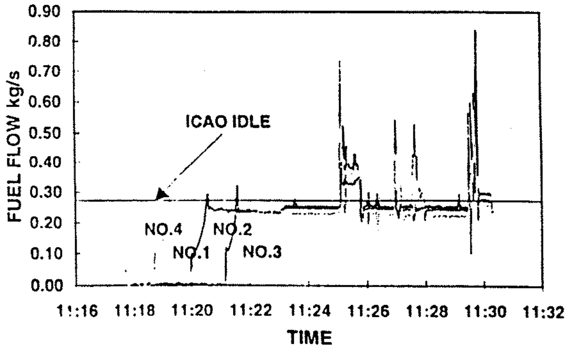
The video recordings give a trace of the ground movement of each aircraft during the period of a data collection visit. Through analysis of the recordings, various taxi parameters relating to an individual aircraft ground movement could be extracted (e.g. the runway exit/push-back time, total taxi duration, total taxi distance, average taxi speed over the total duration, standard deviation of speed over total taxi duration, the number of stops, the holding time of the first stop for departures, the total holding time, the average speed when not being held and the standard deviation of speed when not being held). The time history of heading was also available from the video, allowing a cross-check on the FDR timebase for flight identification. An example heading trace is shown in Figure 1.

FIGURE 1: BOEING 747-236B TAXI OUT
(RB211-524B ENGINES)
HEADING



A modern commercial aircraft FDR records hundreds of parameters but it is possible to extract a selection of parameters from the full list by post-processing the tapes. This was done by BA as a service to the contract. The ICAO Engine Exhaust Emissions Data Bank (EDB) tabulates emissions indices against fuel flow. To enable accurate calculation of emissions the fuel flow per second on each engine is required. In the few cases where fuel flow per engine was unavailable from the FDR, the fan speed (N1%) of each engine and the meteorological data were used to derive it from engine data. Time (GMT) and aircraft heading were also extracted from the FDR as these parameters assisted in synchronising engine running times between the FDR and video data sets. A trace of instantaneous fuel flow is shown in Figure 2.

FIGURE 2: BOEING 747-236B TAXI OUT
(RB211-524B ENGINES)
FUEL FLOW



Data reduction

Assumed Relationship between Engine Exhaust Emissions and Fuel Flow

The amount of engine exhaust emissions (HC, CO and NO_X) depends upon the power setting, engine design characteristics and combustion conditions. Each engine produces different amounts of such pollutants at a given engine power setting. The ICAO EDB reports emission indices per kg of fuel at four representative power settings. With advice from Defence Research Agency (DRA) and other sources (8), this data was curved-fitted for each engine type to predict engine exhaust emissions for any recorded value of fuel flow. This data is stored in the Engine Emissions Spreadsheet.

The database confirms that NO_X emissions are least at idle settings when HC and CO emissions are at their greatest. This poses a problem in determining the HC and CO emissions at low engine power settings. It is well known that some aircraft taxi on engine power settings below the representative idle power setting (7% F_{MAX}). As there is little information available regarding emission indices below the 7% F_{MAX} mode an extrapolation was necessary. Examples of the extrapolations are given in Figures 3.

The emissions of CO_2, SO_2 and H_2O are calculated from simple chemistry as a direct function of the amount of fuel used assuming representative trace elements. For each kg of fuel used, 3.16kg of CO_2, 1.24kg of H_2O and 1g of SO_2 are emitted.

FIGURE 3a - Assumed Relationship between NO_X and Fuel Flow

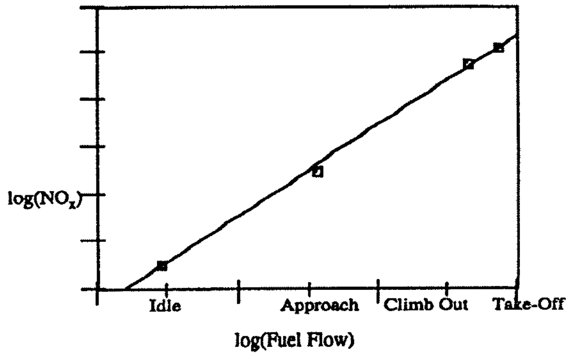


FIGURE 3b - Assumed Relationship between HC and Fuel Flow

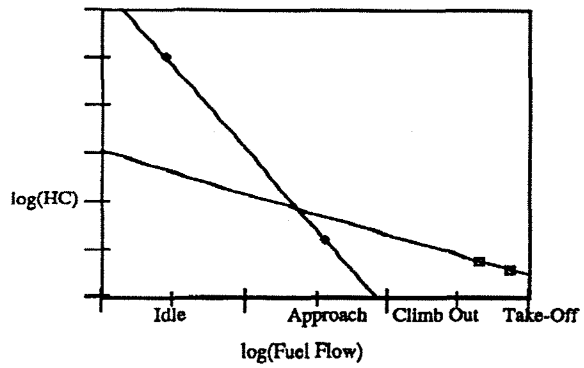
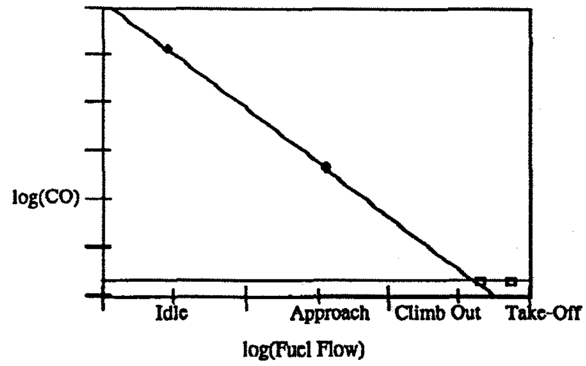


FIGURE 3c - Assumed Relationship between CO and Fuel Flow



Aircraft Ground Movement Fuel Use and Emissions Calculations from FDR Data

Ground movement fuel used and emissions were calculated for all movements for which FDR data were available. An example of the instantaneous hydrocarbon production is given in Figure 4, showing the effect of sequential engine start on a Boeing 747. The calculated fuel use and emissions of individual aircraft ground operation were stored in a Flight Fuel and Emission Spreadsheet. Basic flight details of registration, aircraft type, airline, flight number, stand, scheduled arrival/departure time, push-back/arrival time, engine type, date, runway, entry/exit, taxi path and movement type were recorded for each ground movement with an FDR trace. The engine type reference was used to look-up the appropriate NO_X, HC and CO equations in the Engine Emissions Spreadsheet. An array formula was then used to integrate the emissions of NO_X, HC and CO calculated for the fuel flow per second on each engine. Figure 5 shows the cumulative HC emissions from a Boeing 757, compared with that which would be produced if the ICAO idle setting were used. Total CO_2, H_2O and SO_2 engine exhaust emissions during ground operations were calculated as a direct function of the sum of the total fuel used.

FIGURE 4: BOEING 747-236B TAXI OUT
(RB211-524B ENGINES)
HC EMISSIONS

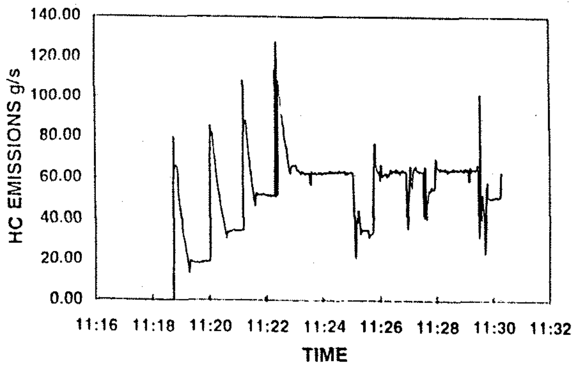
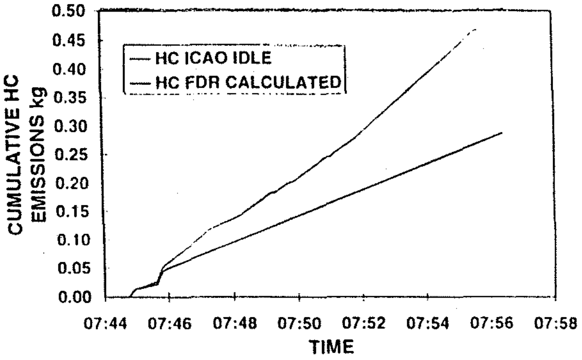


FIGURE 5: BOEING 757-236ER TAXI OUT
(RB211-535E4 ENGINES)
CUMULATIVE HC EMISSIONS



Little information was available on the emission characteristics of engines during start-up. Consequently no emissions were calculated for recorded engine fuel flow of less than 0.04kg/s in this study. This should form the basis for a future study in this area.

Tracking of Aircraft Ground Movement

An attempt was made to use image processing techniques to extract aircraft ground movement coordinate data from the video recordings automatically using the Visilog 4.0 Image Processing and Analysis software. The coordinates of the centre of area of the aircraft radar image could have been used to calculate the track summary statistics. Unfortunately the use of this technique had to be abandoned and manual tracking techniques developed due to the poor quality of the images from the radar screen and the confusion with background data.

Aircraft Ground Movement Database

For each data collection visit two Movement Spreadsheets were created, one for arrivals and one for departures. Each Movement Spreadsheet contained all information extracted from the BAA Apron Control System, together with records made through visual observation of aircraft ground movement and by viewing the video recordings. The fuel use and engine exhaust emission calculation of individual aircraft ground movements from FDR sources stored within a Flight Fuel and Emission Spreadsheet were also referenced in the Movement Spreadsheets. Total fuel (kg) for the taxiing manoeuvre and total emissions of NO_X, HC, CO_2, SO_2 and H_2O were listed. The taxi summary statistics generated from the manual tracking of aircraft ground radar movement traces were transferred to the Movements Spreadsheets listing all movements observed over the period of the study. All non-turboprop powered ground movements records included the precise time of runway exit on arrival or push-back on departure as well as the other movement statistics mentioned above.

The meteorological conditions pertaining at the time the ground movement occurred were recorded in the Meteorological and Airport Status Spreadsheet. Three dummy variables were attached to each ground movement observation, distinguishing visibility, dry/wet and day/night conditions. The visibility dummy variable took the value 0, 1, 2 or 3 dependent upon whether normal visibility operations pertained or whether the operational visibility of the airport had been declared as CAT I, II, or III, respectively. The dry/wet dummy variable took the value of 0 or 1 dependent upon whether it was (or had recently been) raining when the aircraft ground movement occurred. The day/night variable similarly took a value of either 0 or 1, respectively. It had also been the intention to include a wind variable but on each of the data collection days, winds had not exceeded 20 knots and so it was decided to exclude this variable. The other variables were included in the modelling to determine whether inclement weather conditions affect the levels of fuel use and emissions.

The number of taxi heading changes of greater than 90 degrees was also attached to each aircraft ground movement based upon the known taxi path taken by the movement. This variable was included, as it is known from a sub-sample of Engine Emissions Spreadsheet that a change of engine power setting is often required by taxiing aircraft after completion of a turn of 90 degrees. The number of air transport movements in excess of 30 atms per hour at the time of the ground movement was also recorded as an indication of possible taxiway congestion. Familiarity by the pilot with Gatwick was indicated by more than 10 visits per week by the airline.

In order to apply the results from the sampled flights to a complete representation of emissions production at Gatwick, it was necessary to obtain a representative profile of movements over a year. Total air transport movements, split between arrivals and departures during each hour of each day of each month for the months of March 1994 to March 1995, were analysed. Nominal taxi distances in metres were estimated for arrival and departure movements from runway exit to stand and from stand to runway entry. Arrival taxi distances were estimated from all rapid exit taxiways off both runway directions to all available stands. In both cases the most frequent designated taxi path, as used in free flow conditions was assumed. The nominal taxi distance was attached to all observations of aircraft ground movement according to the movement type, runway, exit/entry taken and stand allocated. It should be noted that such distances are not necessarily the same as the taxi distances generated from the manual tracking of aircraft ground movement recorded on video. The variable is included for the modelling of taxi time only, as an indicator of the nominal time to taxi a particular path, aside from factors of congestion or taxi speed.

Modelling

Fuel Use and Emissions Modelling

Multiple regression analysis was performed on the data for each of the aircraft types for which fuel use and emissions from ground operations had been calculated. The dependent variables were fuel used, NO_X, HC and CO. The independent variables were; taxi distance, mean speed over the total distance, the standard deviation of the taxi speed profile, the number of the taxi stops, the moving distance, average taxi speed when not being held, the standard deviation of taxi speed when not being held, the number of 90 degree turns along the taxi path and the total engine lit time.

The total engine lit time could be calculated for each observation, as it was known from the FDR when each engine was shut-down for arrivals and when each engine started-up for departures, with assumptions regarding the number and timing of engines shut-down during taxi-in, the time to engine shut-down once arrived on-stand and the time to engine lit of each engine after push-back. This variable was seen to be very influential. Used as the sole independent variable, it is able to explain in excess of 97% of the variation of fuel used and the three types of pollutant over all aircraft types. Although some of the other independent variables made slight contributions to the explanations of variation of some of the dependent variables, their effect was never statistically significant.

Taxi Time Modelling

As total engine lit time was the dominant variable in explaining variations in fuel used, NO_X, HC and CO, the main thrust of the study then became the development of a model to predict the total engine lit time of aircraft ground movements related to the parameters and assumptions mentioned above.

Two total taxi time models were developed, one for arrivals and one for departure movements. Stepwise multiple regressions with no intercept were again performed. Sample data were taken from the observations for which taxi summary statistics had been calculated. This resulted in a total of 451 observations for the arrival taxi time model and 413 observations for the departure model.
The models of taxi time (in seconds) were derived as:

$$\text{Departures} = 0.2171D + 0.001618M + 30.4F + 243.6W + 155.7U \quad (R^2 = 0.87)$$

$$\text{Arrivals} = 0.1204D + 0.0004242M \quad (R^2 = 0.87)$$

where:

D is the nominal taxi distance (m)
M is the maximum take-off mass (kg)
F is the movement rate on the runway greater than 30 per hour i.e. F = ATM/hr -30
W is 0.0 for dry runway, 1.0 for wet runway.
U is 1.0 for less than 10 flights per week by the airline, or 0.0 if 10 flights or more per week.

The 'excess of 30 atms in the hour of the movement' variable is only present in the departure model. This was to be expected because departures are much more likely to be delayed in ground movement than arrivals as the number of air transport movements handled increase. The model predicts that 40 atms in the hour will on average delay all departures by 304 seconds and 50 atms in the hour by 608 seconds. It is suspected that the congestion effect would be greater at airports less subject to flow control. If the operator of the movement has less than 10 flights per week into Gatwick Airport, implying the possibility that the pilot is relatively unfamiliar with the taxiway layout, the model predicts that this increases departure movement taxi times by 156 seconds. Wet conditions also appear to increase departure taxi times by 244 seconds.

Experience at Munich agrees in general with this model based on Gatwick: take-off taxi takes approximately twice as long as landing taxis and larger aircraft take longer than small aircraft (9) - though the Munich results are not normalised for taxi distance.

Application of Model

The fuel use, emissions and taxi time models were used to estimate total annual fuel use and emissions of aircraft ground operations at Gatwick Airport. It should be noted that the developed grossed-up model only applies to commercial and non-turboprop aircraft ground movements.

As a result of the dominance of the total engine lit time variable in explaining the values of fuel used, NO_X, HC and CO, it was decided to use this variable solely in the estimation of total grossed-up fuel use and emissions. In simple regression models of fuel use with total engine lit times as the only independent variable, the coefficient estimate is synonymous with the true average engine idle fuel flow. Where no information was available regarding the true engine idle fuel flow of particular engines, the figure was estimated assuming a fixed percentage less than the idle reported in the ICAO Data Bank.

The grossed-up model utilised all the observations of aircraft ground movements over the whole day collected for the dates of the visits. Each observation was then weighted to annual values with individual weightings calculated for each aircraft type. The percentage of each aircraft type observed matched the percentages of each aircraft type over the whole year.

It is the case that airlines have preferences for, or are constrained to the use of, a small group of stands. Thus, aircraft type/airline/engine type observations were assigned to one of a small number of 'mean' stands. Nominal taxi distances were then calculated to such 'mean' stands for the weighted aircraft type/airline/ engine type combinations.

To calculate nominal taxi distances to 'mean' stands, knowledge was also required of the runway used, runway entry point for departures and rapid exit taxiway taken for arrivals. To account for runway use all weighted aircraft ground movement observations were split 70/30 between the use of 26L/08R. For convenience it was assumed that all departures used the extreme entry points of the runway. For the movements observed, a probability distribution was established of the use of the first, second and third runway rapid exit taxiways for each aircraft type. Where there were no observations for a particular aircraft type the probability distribution for a similar class of aircraft were assumed. Thus, the grossed-up model apportioned the taxi distances of annual weighted aircraft type/airline/engine type/'mean' stands by assumed use of runway and entry/exit points used over the year.

The computation of total engine lit times from estimates of total taxi time required assumptions regarding the number and timings of engines shut-down during taxi-in, the time to engine shut-down once arrived on-stand and the time to engine light of each engine after push-back. The engine light procedures of aircraft types were estimated from those observed from the FDR extracts. The average time of engine shut-down after runway exit if shut-down on taxi-in; the average number of engines shut-down before on-stand; the average engine shut-down time after on-stand; and the average time after push-back to start-up of each engine were determined. It should be noted that an engine of an inbound aircraft will occasionally be cut just before arriving on-stand. Thus, the times of engine shut-down for these aircraft types should be treated with caution. Due to this fact and because of the large number of observations of the 737-200, the 737-200 estimate of the average engine shut-down time after on-stand of 28.9 seconds was used for all aircraft types.

Obviously airlines will have different shut-down and start-up procedures for aircraft types within their fleets. To ascertain the engine light procedures during taxi-in and taxi-out of airlines, a questionnaire was sent to all major airlines operating turbofan aircraft at Gatwick Airport. A total of 36 completed questionnaires were received out of a total of 61 sent out. The results of this questionnaire revealed that the vast majority of departures do not start any engines until push-back approval has been given and they have all engines lit before taxi approval. The questionnaire also asked whether any engines are shut-down during the taxi-in to stand and if so how many remained lit. The results from this question were incorporated directly into the model application for each known airline/aircraft type procedure.

Table 1 gives the model estimates of the annual Gatwick Airport aircraft ground movement fuel use and emissions '94-'95. These estimates were based upon the following data: (1) The average true idle fuel flow of engines in aircraft with available FDR data, sourced from British Airways, Propulsion. These were used for all such engines. (2) For all other engines the ICAO idle fuel flow was factored by the average percentage by which the true idle flow was less than the ICAO idle fuel flow for the FDR sample of engines. (3) By analysis of the air transport movements over the year it was found that in hours with more than 30 atms, the average number of atms in the hour is 36.67. A total 59% of all atms occur in hours with more than 30 atms in the hour. (4) From an analysis of the meteorological conditions existent on the data collection visits it was found that Gatwick Airport had wet conditions 14.2% of the time.

Table 1 also gives the fuel use and emissions assuming the ICAO fuel flows and the LTO Cycle (26 minutes taxi ground idling for a complete aircraft turnaround, of which 7 minutes taxi-in and 19 minutes taxi-out).

TABLE 1- Estimates of Annual Gatwick Airport Aircraft Ground Movements Fuel Use and Emissions 94-95 (Tonnes)

	Model	ICAO Cycle
Total Fuel	24,233	41,857
Total CO_2	76,577	132,268
Total H_2O	30,049	51,903
Total SO_2	24	42
Total NO_X	77	155
Total HC	632	558
Total CO	1,399	1,511

Conclusions

A methodology has been developed to identify the factors controlling aircraft fuel use and emissions production during ground movements. This has involved the use of Flight Data Recording (FDR) records of engine setting, the recording of aircraft taxi movements as indicated on a ground movement radar screen and the recording of a number of other background variables.

The application of the methodology at Gatwick showed that fuel use and emissions production are related directly to the time during which the engines are lit, as well as the characteristics of the engines themselves.

The engine lit time is itself closely related to the taxi time. The main factor controlling the taxi time is the taxi distance. Other secondary factors affecting departure taxi time are the mass of the aircraft, the weather, the number of movements per hour and the pilots' familiarity with the airport. Of those secondary factors, the aircraft mass was the only one to affect arrival taxi times.

The idle engine settings observed from the FDR data were substantially below the 7 percent setting used in the ICAO Landing and Take Off (LTO) cycle. This resulted in lower fuel flows per minute than the LTO cycle and hence lower emissions per minute except for Carbon Monoxide (CO) and Hydrocarbons (HC). These were higher than the LTO cycle assumptions would suggest, due to the lower combustion efficiency. The validity of these results depend on the assumptions as to the shape of the relationship between engine settings and emissions at very low power settings, the evidence for which is sparse.

The statistical models of fuel flow and emissions were applied to the movements at Gatwick over the year, assuming that those movements for which FDR data was not available used a similarly low engine setting. The combination of these relatively low settings and the shorter taxi times relative to the ICAO LTO cycle, resulted in estimates of total fuel use which were approximately 60 percent of that inferred by the LTO cycle. The production of HC and CO was however of the same order as the LTO cycle would predict, though the reasons for the production were different.

The models are in principle capable of application to other airports, given a knowledge of average taxi times, congestion characteristics weather and aircraft fleet mix. It would, however, be necessary to verify their applicability at some other airports with characteristics different from those at Gatwick.

Further work is necessary to establish the shape of the relationship between engine setting and emissions at low power. It is also necessary to assess the emissions output during the start-up cycle: it may be equivalent to all other ground emissions by aircraft.

References

1. Fan, Henry S.L.; 'Fuel conservation by controlling aircraft ground operations', Transportation Planning and Technology, 1990, Vol. 15, pp.5-11.
2. Ciaralli-Parenzi, Giorgio; 'Reverse gear is being considered', letter to Flight International, 14 June 1995, page 82.
3. Air Transport World, September 1995, page 49.
4. Haglund, Richard; 'Fixed air systems are more economical than APUs', Airport Forum, No.5, 1991, pp.69-73.
5. Raper, D.; 'Air quality monitoring', lecture to Short Course in Airports and the Environment, Department of Aeronautical and Automotive Engineering and Transport Studies, Loughborough University, 9-12 May, 1995.
6. Renz, E.; 'Case study 1: Munich Airport', lecture to Short Course in Airports and the Environment, Department of Aeronautical

and Automotive Engineering and Transport Studies, Loughborough University, 9-12 May, 1995.

7. 'ICAO engine exhaust emissions data bank', 1st ed., International Civil Aviation Organisation, Doc. 9646-AN/943, Montreal 1995.

8. Martin R.L., Oncina C.A. and Zeeben J.P.; A simplified method for estimating aircraft emissions, ASME/IGTI Conference, Netherlands, 1994.

9. Hergt, V.; Personal communication, 10 May 1994.