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Analysis of Departure and Arrival Profiles Using Real-Time Aircraft Data

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The quantity and rate of fuel burned during aircraft operations forms the basis of all emission inventories at airports. The international standard for calculating fuel burn and emissions produced is the landing and takeoff cycle of the International Civil Aviation Organization and forms the basis for many emission inventory models and emission charging schemes at airports. The acquisition of real-time aircraft flight data recorder information provided a unique opportunity to compare actual operational fuel flows and times in mode to the International Civil Aviation Organization standard. For departures, there is tremendous variety in fuel flow patterns, rates of fuel flow, and times in mode. Only 67% of the flights analyzed show a classic transition from takeoff to climbout. Most of the remaining flights showed essentially flat-line fuel flow profiles. All aircraft showed some fuel flow rates indicative of reduced-thrust departures. The certificated values for departure fuel burn matched favorably to the real-time totals for four-engine aircraft. However, for the twin-engine aircraft in this study, total departure fuel burn was grossly overpredicted, due to shorter observed departure times in mode. The average approach times in mode were slightly higher than the International Civil Aviation Organization norm, but approach fuel flow rates were significantly lower, yielding lower total fuel burn values. In general, total fuel burn for both departures and arrivals is overestimated by the International Civil Aviation Organization method.

Introduction

THE quantity and rate of fuel burned during aircraft operations forms the basis of all emission inventory work at airports. The amount of pollutants produced is a function of the fuel flow rate, emission indices for the pollutant, and time, per mode of operation. The mass of radiatively active (greenhouse) gases generated is a function of the total fuel used multiplied by the emission coefficients for the gases in question (e.g., carbon dioxide CO_2 and nitrous oxide N_2O [1]). Similarly, the quantity of sulfur dioxide (SO_2) is determined by total fuel burn and the emission coefficient.

The internationally recognized standard for calculating the fuel burn and emissions produced in emission inventory work is the landing and takeoff (LTO) cycle of the International Civil Aviation Organization (ICAO) [2]. The LTO cycle was first developed in the late 1960s and early 1970s [3]. This LTO cycle forms the basis for many other emission inventory models now in use at airports (e.g., [4]). Other models in use (e.g., the U.S. Federal Aviation Administration's Emissions and Dispersion Modeling System) derive fuel flow rates and times in mode through performance-based modeling. All methods for emission calculation use the ICAO Engine Emissions Databank of fuel flow rates and emission indices [5].

The quantity of fuel burned and emissions produced by aviation is attaining growing significance. For instance, the European Union (EU) has passed legislation to include airlines in the EU Emissions Trading Scheme from 2012. This will apply to an entire flight, of which LTO fuel burn has varying proportions, depending upon flight length. Some European airports (e.g., in Switzerland and Sweden) have LTO emission charging schemes already in place. In the United States, airports planning federally funded expansions must meet local air-quality conformity standards for the funds to be issued. Therefore, there are serious economic and regulatory reasons for knowing how well current inventory models predict fuel and emission amounts.

The acquisition of real-time aircraft flight data recorder (FDR) information by the Environmental Measurement and Modeling Division of the Volpe National Transportation Systems Center provided a unique opportunity to evaluate fuel flow rates, times in mode, and total fuel burn and to compare it with the values for the ICAO certification standard. The acquired database includes measured fuel flow rates and operating times among the 105 parameters.

The purpose of this paper is to calculate and compare values associated with aircraft departures and arrivals for a specific suite of aircraft/engine combinations, comparing ICAO certification values of time in mode, fuel flow rates, and LTO fuel consumption with observed data collected from FDR. Although this research is based on a few thousand flights and millions are made each year, nonetheless, the results from this analysis provide a first step in analyzing how well current methods are modeling aircraft operations and fuel burn at airports. Comparison of these data with performance-based models is part of an ongoing complementary project.

ICAO Standard LTO Cycle

Aviation emissions at airports are generated by aircraft during LTOs. This cycle has been studied for engine certification procedures and the standard reference cycle has been determined (Table 1) [2]. The LTO cycle has four modes: takeoff, climbout, approach, and taxi-idle queue. Aircraft engines operate at different power levels

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Table 1 ICAO standard LTO cycle

Mode	Power setting, $\%F_{oo}$[a]	Time in mode, min
Takeoff	100	0.7
Climbout	85	2.2
Approach	30	4.0
Idle	7	26.0

[a]F_{oo} is the rated output of the engine, measured in kilonewtons.

during the various modes. Fuel consumption and the production of emissions vary with the power setting. The fuel flow rates and emission indices are verified during the engine certification process, and these data for all engines are in the ICAO Engine Emissions Databank [5].

The engine certification process began in the late 1960s and early 1970s [3]. The LTO cycle was developed based on studies of the fleet operating at the time. This was principally a fleet of four-engine commercial jet aircraft (e.g., the Boeing 707). The ICAO LTO operating cycle has not been revised since that time, although the global fleet has changed considerably and is now dominated by twin-engine aircraft.

Methodology

FDR Database

A total of 2824 flight records were examined. The majority of the records begin with the departure from one airport and end with the arrival at the gate of a second airport. The data were from 5 different airlines, with 14 unique aircraft/engine combinations, at 80 airports on 5 continents, with a wide range of latitudes and altitudes. The airlines are a mix of legacy carriers, international carriers, charter, and domestic regional carriers.

The FDR information was delivered in spreadsheet format. Two sets of files were acquired; the flight files contained information about the aircraft flights, including the aircraft type, origin/destination airports, airport elevation, takeoff and landing runway identification, and length. The events files contained the measured data recorded onboard the aircraft during flight and had 105 data columns.

Engines were matched to the aircraft through different processes. Three airlines gave the engine name and the unique identification (UID). For the other two airlines, the engine for the aircraft was found in [6]. When there were two UIDs for a specific engine in [6], it was ascertained that the difference between the engines was in the emission indices, whereas the fuel flow rates were the same. The aircraft/engine combinations for this study are in Table 2.

Data Analysis

The analysis was done on a segment-by-segment basis. The first step was to break the flight records apart into pieces corresponding to LTO cycle divisions. Mixing height is not a variable in this study, and therefore the ceiling for the LTO was held at the default 3000 ft above ground level (AGL) for departures and arrivals.

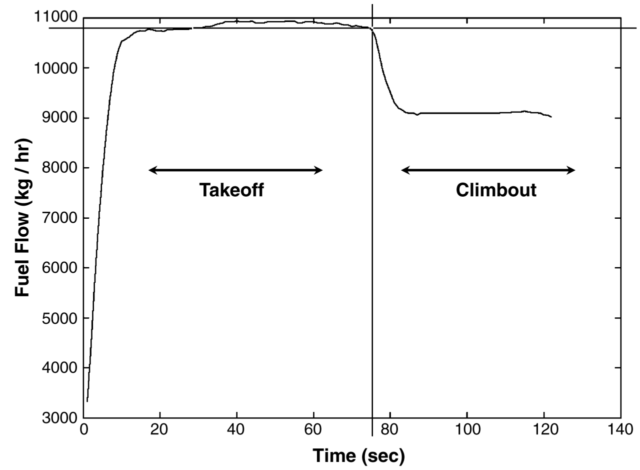

Fig. 1 Sample screen shot showing a classic ICAO-style fuel flow profile and cursor marking the takeoff/climbout transition point.

The flight records begin with first engine startup, and this indicates the beginning of the taxi-out/idle/queue segment. The end of taxi-out and beginning of takeoff is identified by the start of takeoff roll, and in the events file, this is marked by the commencement of recording the ground-track distance from the start of takeoff. Analyses stop at 3000 ft AGL, and for the purposes of this study, 3000 ft AGL was defined as the altitude of the runway at the start of takeoff roll plus 3000 ft. The Global Positioning System (GPS) pressure altitude column was used for altitude.

The approach segment begins at 3000 ft AGL; in this case, the boundary is 3000 ft above the altitude of touchdown. Taxi-in begins at the end of the landing roll. Note that this data set did not include the landing roll, and there was typically a gap of 30–45 s in the events file. The flight record and taxi-in segment ends at the gate with engines off. The current analysis is restricted to departures and approaches; the ground portions of the LTO cycle form a separate study, currently underway.

The definition of the transition from takeoff to climbout modes in the LTO cycle is a throttle back on the engine and attendant fuel flow drop. It was determined that the best way to break the flight record from takeoff to climbout was to use fuel flow time-history data. For this, the MATLAB [7] commercial software was used. The separation of takeoff and climbout was done manually using fuel flow profiles plotted using a visualization subroutine in MATLAB (Fig. 1).

Fuel flow from the start of takeoff roll to 3000 ft was plotted vs time for each flight record for each aircraft type in the FDR database. The transition from takeoff to climbout was chosen using the mouse and cursor on the graph at the point of inflection from higher-to-lower fuel flow, and the departure was split into the two segments. The rest

Table 2 FDR aircraft and engines

Aircraft	Number of engines	Engine	Engine UID	MTOW, kg
ARJ85	4	LF507-1F	1TL004	43,998
ARJ100	4	LF507-1F	1TL004	46,039
A319-112	2	CFM56-5B6/2P	3CM022	64,000
A320-214	2	CFM56-5B4/2P	3CM021	73,500
A321-111	2	CFM56-5B1/2P	3CM020	83,000
B757-200	2	RR RB211-535E4	3RR028	106,594
B767-341	2	GE CF6-80C2B7F	2GE055	186,880
A330-202	2	GE CF6-80E1A4	4GE081	230,000
A330-223	2	P&W 4168A	4PW067	230,000
A330-243/1	2	RR Trent 772B-60/16	2RR023	233,000
A330-243/2	2	RR Trent 772B-60/16	3RR030	233,000
A340-313	4	CFM56-5C4/P	2CM015	275,000
B777-300ER	2	GE90-115B1	7GE099	344,549
A340-541	4	RR Trent 553	8RR044	372,000

Table 3 Departure fuel flow types and model of aircraft[a]

	Departure fuel flow types								
Aircraft	1	2	3	4	5	6	7	8	Sum
ARJ85	3	0	0	0	**25**	4	0	0	32
ARJ100	34	19	11	0	**107**	31	0	0	202
A319-112	64	1	0	36	0	0	0	**86**	187
A320-214	**146**	2	0	1	0	0	0	86	235
A321-111	**87**	0	0	0	0	10	0	29	126
757-200	**147**	6	0	8	14	0	0	0	175
767-300 ER	39	7	28	45	16	**49**	0	1	185
A330-202	72	**89**	0	0	3	0	0	0	164
A330-223	**250**	1	0	0	0	0	0	3	254
A330-243 No. 1	**10**	0	0	0	0	0	0	0	10
A330-243 No. 2	32	8	0	**121**	24	1	0	0	186
A340-313	67	0	0	0	3	**88**	0	26	184
777-300ER	**249**	9	1	0	0	4	0	0	263
A340-541	2	0	1	0	6	1	**144**	0	154
Totals	1202	142	41	211	198	188	144	231	2357
%	51.0	6.0	1.7	9.0	8.4	8.0	6.1	9.8	100

[a]Bold denotes the most common type of fuel flow pattern.

of the flight segments were divided automatically by the program written in MATLAB [7] using the parameters described previously. The flight segments were saved to comma-separated files (.csv).

Each flight record has a unique flight record number, and this was held with the data. All information from the original events files (e.g., fuel flow rates, time, altitude, and aircraft weight) was preserved in the .csv files.

A second subroutine was written in MATLAB [7] to tabulate and extract data needed from the .csv segment files. Tables were created in spreadsheet formats that contained summary data for each segment for each flight by flight record number, named the TIM (time-in-mode) files. Data extracted included aircraft weight at the start of takeoff roll and summed the values of fuel consumed and total time for each segment.

The tabulated data in the TIM files were then analyzed for simple descriptive statistics. The data analysis subroutine in Microsoft Excel was used. Mean, first standard deviation in a 95% confidence interval, maximum, and minimum values were derived and compared with the ICAO standards. The results are presented in the next section.

Results: Departure

Fuel flow data from all 2824 flights were run through the MATLAB [7] program, and of these, 2357 were usable records. Unusable records were those that began at midflight, had broken or discontinuous columns, or were otherwise corrupted files (e.g., the altitude recorder would stick at one number and then abruptly transition to a much higher altitude).

When designing the fuel flow analysis program, the assumption was made that the transition from takeoff to climbout modes (e.g., as depicted in Fig. 1) would be seen in all fuel flow records. It became apparent during the analysis of the flight data that there exists a wide variability in patterns of fuel flow in departure. Some fuel flow data do not show a classic takeoff/climbout profile and therefore cannot be broken into segments, because there is no discernible change from takeoff to 3000 ft AGL. This meant that time-in-mode values for takeoff and climbout could not be derived, and instead, only total departure time was available for analysis.

Departure Fuel Flow Patterns

A classification scheme for departure fuel flow patterns was developed, and each usable departure was classified. Eight distinct patterns were recognized. Most aircraft have a typical form to their fuel flow during departure, but even within one aircraft/engine combination there can be variability. Note that each aircraft/engine combination in Table 3 was operated by a single airline; the differences in fuel flow types within each aircraft type are not due to different airlines' operational procedures. Fuel flow types by model of aircraft are shown in Table 3. Bold numbers indicate the statistical mode for the type of fuel flow pattern for that aircraft. The departures are grouped by those that show a classic ICAO profile (group I), those that do not (group II), and the unusual group III (Table 4).

Departure fuel flow types 1, 2, and 8 are illustrated in Fig. 2. Within these fuel flow patterns, it is possible to identify a change in the rate of fuel flow that indicates a configuration change, usually throttle back. Type 1 shows the classic ICAO profile. There can be a wide range in the magnitude of decrease in fuel flow at the transition from takeoff to climbout (∼5 to 30%). If the transition time at the decrease in fuel flow rate was greater than 15 s, then the pattern was classified as a type 4 or 6 (discussed further subsequently). Type 2 also shows the classic ICAO profile, with a pronounced decrease in fuel flow from takeoff to climbout, but is then marked by a further decrease and fluctuations in the fuel flow rate. This pattern is ascribed to air traffic management procedures and is discussed subsequently in the section on departure time in mode. Type 8 is most common in the A319-112 and A320-214 aircraft. This fuel flow profile consists of a sharp initial peak in fuel flow, then a gradual decline, with a distinct drop in fuel flow rate, indicating a configuration change. The magnitude of fuel flow drop at the takeoff/climbout transition in type 8 is generally less than that seen in types 1 and 2.

Fuel flow type 7 (Fig. 2) was seen exclusively in the A340-541. This pattern is marked by an inflection point in fuel flow rate about midway through departure, but is unique in that there is an increase in fuel flow rate and not the usual decrease. To answer the question as to the reason for this, flights were selected for analysis based on a range of geographic distribution and fuel flow rates. The parameters of fuel flow, thrust lever angle, average N1,** GPS pressure altitude, and calibrated air speed were extracted from the .csv files and plotted against time to 3000 ft. The results of this analysis are discussed in the section on departure fuel flow rates.

Departure fuel flow types 3, 4, 5, and 6 are illustrated in Fig. 3. These patterns do not show the classic takeoff/climbout profile and therefore cannot be analyzed for a change in mode, because there is no discernible point of inflection in the fuel flow rate. The classification of these four types is based on differences in the shape of the profile. All four show an initial increase in fuel flow at the start of takeoff roll followed by variations in the profile. Type 3 shows a uniform flat line all the way to 3000 ft. Type 4 shows a slight increase and then slow decrease during departure. Type 6 shows a gradual decrease in fuel flow rate throughout the departure. Type 5 is similar to type 2 in that there are fluctuations in fuel flow rate throughout the departure, and it is also attributed to air traffic management. All four of these fuel flow patterns generally occur at less than 100%-rated fuel flow and are probably reduced-thrust departures.

**N1 is the rotational speed of the outer (or lower-pressure) spool of a turbofan engine. It is usually expressed as a percentage of the maximum speed of this spool under International Standard Atmosphere (ISA) conditions.

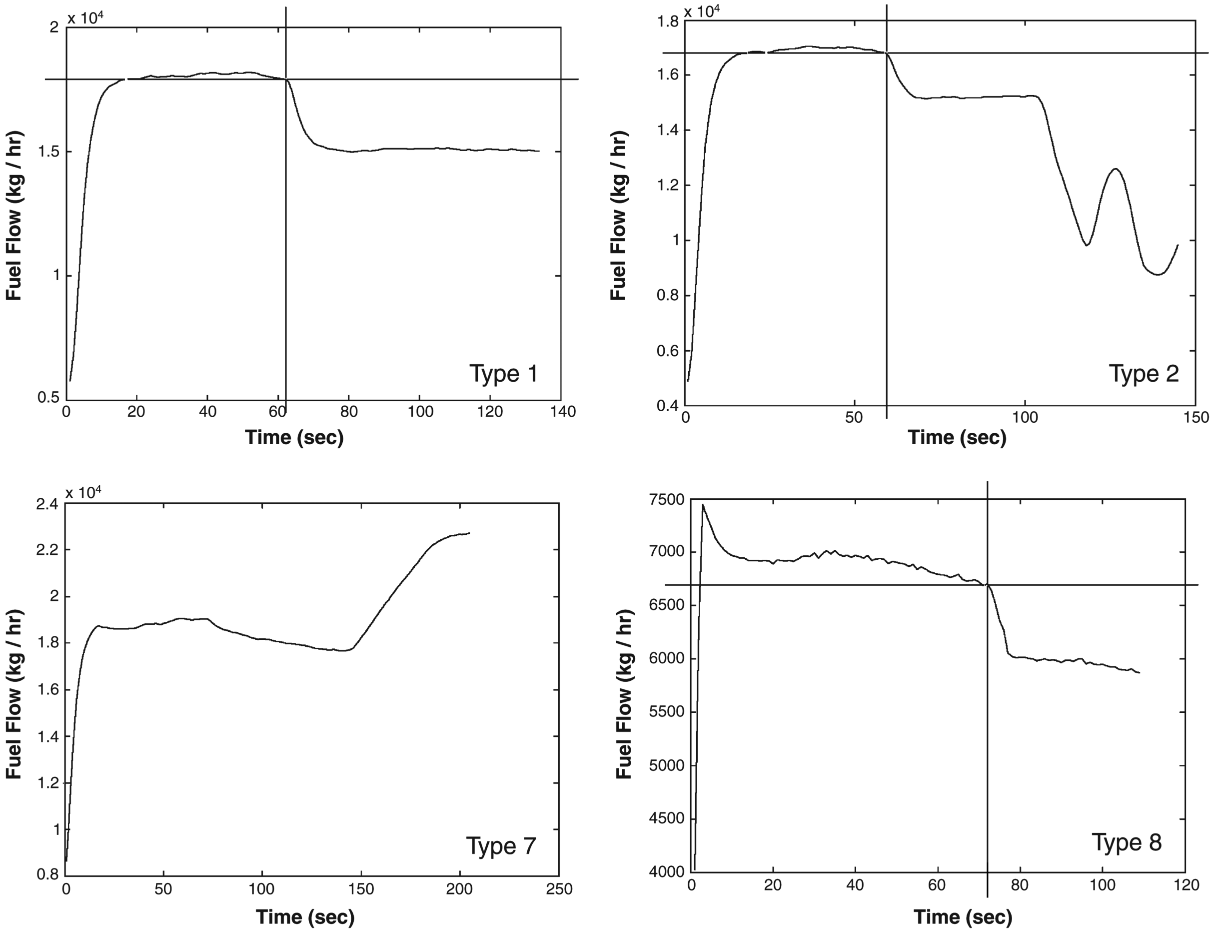

Fig. 2 Departure fuel flow types 1, 2, 7, and 8.

Departure Fuel Flow Rates

Departure fuel flow profiles were analyzed by pattern for each aircraft. The overall results for each aircraft are presented in Fig. 4. On average, FDR fuel flow rates were just slightly below the ICAO values for that engine. There are two notable exceptions in which measured FDR fuel flow rates in departure were at least 10% higher than the ICAO standard, and this is discussed subsequently. There were also three cases in which the ICAO value was significantly above the average FDR fuel flow. Fuel flow rates varied primarily by type of takeoff profile and are subsequently discussed by fuel flow classification group.

Group I consists of fuel flow types 1, 2, and 8, which show a transition from takeoff to climbout. In these takeoffs, the fuel flow rate generally ranges from around 90 to over 100% of the ICAO maximum for each engine. The most extreme example of average fuel flow rates over the ICAO maximum is seen in the A319 and A330-223. Climbout values for type 1 profiles are typically similar to the ICAO values, at around 75–80% of maximum fuel flow rate. The lowest examples of type 1 fuel flow rates are seen in the A330-243/1, in which the takeoff and climbout fuel flow rates are both lower than the ICAO standards. Type 2 takeoff fuel flow values are similar to type 1, usually very slightly over the ICAO maximum value. The big difference is seen in the climbout mode, with type 2 values fluctuating greatly, from around 80 down to 30–50%, with a value at 20% of the ICAO maximum during a B777 departure. Type 8 departures typically show both takeoff and climbout at lower numbers than the ICAO values, with takeoffs at 85–100% and climbouts at 75–80% of ICAO data.

Group II consists of fuel flow types 3, 4, 5, and 6. These departures do not have a distinct takeoff to climbout transition. With just a few exceptions, these departures all occur at fuel flow rates below the ICAO maximum certificated value for the engines. The fuel flow rates are generally seen between 70–85% of the ICAO maximum for each engine. Exceptions to this were seen, with extremes at both ends. For example, one type 6 flight for the B777 occurred at approximately 105% of the ICAO value (but with very short duration). One type 3 flight took place at 60% of maximum fuel flow for that engine.

The most unusual fuel flow pattern, Group III's type 7 for the A340-541, was examined in detail, as described in the section on departure fuel flow patterns. All type 7 profiles show initially constant fuel flow and airspeed, which then increase with an increase in N1. Significantly, most type 7 profiles occur at airports in hot, low latitudes. All fuel flow rates in the flights examined started at approximately 60–65% and increased to 70–75% of ICAO-certificated 100% takeoff fuel flow for this engine. This takeoff sequence is consistent with reduced-thrust takeoff procedures given by Airbus for the A340-500/-600 family. Airbus allows a reduced thrust for the A340-500 of 40%; this low takeoff power is below the climbpower setting, and so the engine power setting must be advanced during the transition from the reduced-thrust takeoff power to the climb-power setting [8]. Airbus states that these procedures allow the use of lower minimum control speeds and hence lower V_1 takeoff decision speeds.

Discussion

One notable result from this analysis is the fact that for all aircraft but two (A330-202 and A330-243/1), there were instances in which the measured FDR fuel flow rate exceeded that of the certificated ICAO engine data (Table 5). There are several potential reasons for this.

The ICAO-certificated values are corrected to standard ISA values and do not take into account changes in altitude and meteorology. The ICAO certification is done using full-scale engines on a test stand, and thus the installation effect on the aircraft is not taken into account. Furthermore, the values in the ICAO databank are averages and do not show the variance present during measurement. For

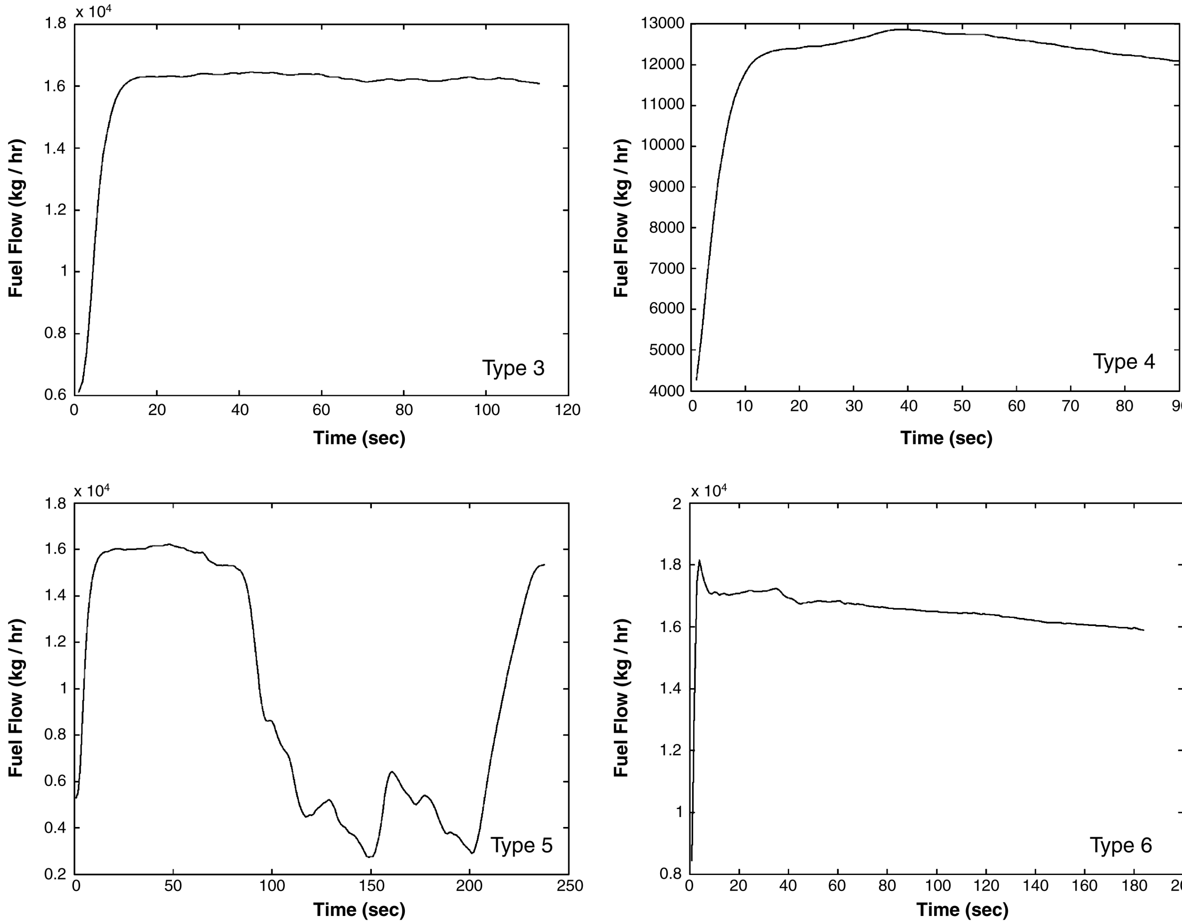

Fig. 3 Departure fuel flow types 3, 4, 5, and 6.

example, Pratt and Whitney, a major manufacturer of aircraft turbine engines, shows a tolerance band of about ±5% on certification fuel flow [9]. For the engine to be in an acceptable condition, all engine parameters must fall within their respective tolerance bands. Therefore, a similar range of fuel flow data in the FDR data could reasonably be expected.

Certification tests are done on new engines and do not consider wear and tear on the engine or airframe [3]. As the airframe ages, it can deteriorate, and airframe deterioration increases drag and therefore also affects fuel consumption [3,10]. It has been estimated that 1–2% increased airframe drag can mean 1–2% increased fuel burn [3].

The main components involved in engine deterioration are compressor aging and turbine degradation [10]. When engine components wear, fuel flow must increase to maintain the required thrust level [3]. The time between maintenance on an engine also has

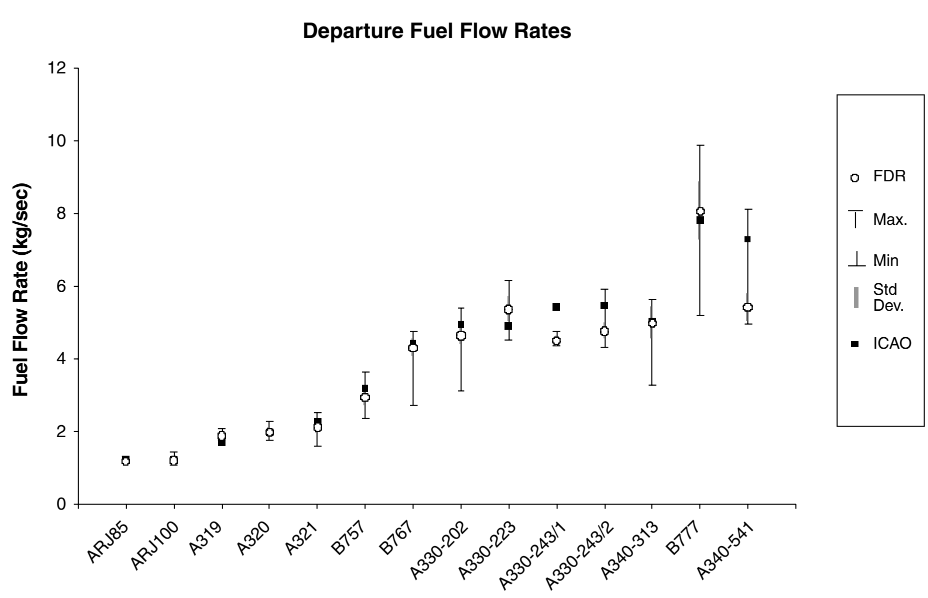

Fig. 4 Comparative fuel flow rates.

Table 4 Classification of departures by general fuel flow patterns

Group	Types	No. of departures	% of total
I	1, 2, 8	1575	66.8%
II	3, 4, 5, 6	638	27.1%
III	7	144	6.1%

a measurable impact on fuel flow rates. Over the on-wing maintenance cycle, there can be a reduction in engine component efficiency and a corresponding fuel burn increase [3]. There have been estimates that the effect of engine aging and position in the maintenance cycle can increase specific fuel consumption from 4–10% [10]. With the rapid rise in fuel prices, airlines are working hard to improve their fuel consumption; some airlines have now incorporated engine washing into their maintenance practices [11].

Finally, the airlines have discretion on how they fly their planes. The aircraft that had the most departures over 100% fuel flow (Table 5) did this at airports in hot, low latitudes and at an airport that was essentially at ISA conditions. For whatever reason, this airline chose to make hard, fast departures with their B777s. Interestingly, the odd type 7 departures of the A340-541 are made by this same airline.

The other variations in fuel flow involve types 2 and 5, which show the lowest fuel flow rates and also the longest departure times (discussed subsequently). These are interpreted as long, slow departures and are probably due to air traffic management issues. They may also be done to keep operating engine temperatures low for reasons of engine preservation. Group III departure types 3, 4, 5, and 6 virtually all occur at fuel flow rates significantly less than the ICAO maximum and are interpreted as reduced-thrust departures.

Departure Times in Mode

Departure times in mode were analyzed by aircraft type and fuel flow profile. The results for types 1, 2, and 8 for takeoff and climbout are tabulated in Tables 6 and 7, and total departure times are illustrated in Fig. 5.

For all takeoffs of type 1, and 8, and most type 2 takeoffs, the ICAO takeoff time is less than the FDR-measured time in mode. Only with type 2 departures of the B757 was the ICAO value greater than the FDR value. For climbouts, the ICAO time in mode is always much greater than the FDR value.

Total departure times for all fuel flow types are illustrated in Fig. 5. The aircraft are plotted on the x axis from the lowest-to-highest minimum takeoff weight (MTOW). The mean FDR time to 3000 ft is less than the ICAO standard for all aircraft except the A340. Both the A340-313 and A340-541 took more time, on average, than the ICAO standard. Other aircraft do have instances in which they take longer than 174 s to reach 3000 ft, but for all aircraft except the two

Table 5 Tabulation of departures with fuel flow rates over 100%

Aircraft	No. of flights over 100% fuel flow	No. of valid flight scripts	Percentage of valid flights over 100% fuel flow
B757	6	175	3.4
B767	1	185	0.5
B777	184	263	70.0
ARJ85	3	32	9.4
ARJ100	33	202	16.3
A319	59	187	31.6
A320	30	236	12.7
A321	8	125	6.4
A330-202	0	164	0.0
A330-223	149	254	58.7
A330-243/1	0	10	0.0
A330-243/2	2	186	1.1
A340-313	11	184	6.0
A340-541	2	108	1.9

Table 6 Takeoff time in mode for fuel flow types 1, 2, and 8

	Takeoff	FDR takeoff time, s						
Aircraft	Fuel flow type	Number of data sets	Mean	Standard deviation	Maximum FDR value, s	Minimum FDR value, s	ICAO takeoff time, s	ICAO% of FDR
ARJ85	1	3	72.6	7.5	80.75	66	42	57.9
ARJ100	1	34	71.8	21.2	106.75	2	42	58.5
ARJ100	2	19	70.8	13.5	96	43	42	59.4
A319	1	64	66.0	4.8	78	49	42	63.7
A319	8	85	69.4	5.6	83	56	42	60.5
A320	1	147	68.0	5.8	85	54	42	61.8
A320	8	86	72.3	6.2	89	55	42	58.1
A321	1	86	74.3	6.9	92	52	42	56.6
A321	8	29	78.1	6.9	91	65	42	53.8
B757	1	147	72.0	9.7	101	13	42	58.3
B757	2	6	61.8	8.3	88	34	42	68.0
B767	1	39	61.5	5.4	77	48	42	68.3
B767	2	7	63.1	6.3	76	57	42	66.5
A330-202	1	72	82.0	11.0	97	23	42	51.2
A330-202	2	89	81.6	9.7	100	51	42	51.4
A330-223	1	250	83.4	7.6	102	63	42	50.4
A330-243/1	1	10	70.7	5.5	76	57	42	59.4
A330-243/2	1	32	78.0	12.3	100	53	42	53.8
A330-243/2	2	8	78.9	6.3	85	66	42	53.2
A340-313	1	67	125.1	14.3	149	72	42	33.6
A340-313		26	129.3	20.8	152	36	42	32.5
B777	1	249	53.4	8.3	81	36	42	78.6
B777	2	9	54.2	6.9	72	50	42	77.5

Table 7 Climbout time in mode for fuel flow types 1, 2, and 8

Aircraft	Climbout Fuel flow type	Number of data sets	FDR climbout time, s Mean	FDR climbout time, s Standard deviation	Maximum FDR value, s	Minimum FDR value, s	ICAO climbout time, s	ICAO as % of FDR
ARJ85	1	3	56	15	68	39	132	237.1
ARJ100	1	34	60	33	130	13	132	220.8
ARJ100	2	19	112	26	177	78	132	118.1
A319	1	64	26	6	50	16	132	501.7
A319	8	85	28	5	44	16	132	478.9
A320	1	147	30	6	44	15	132	433.6
A320	8	86	30	6	44	13	132	438.3
A321	1	86	40	8	59	17	132	331.1
A321	8	29	34	4	43	26	132	385.5
B757	1	147	39	14	95	12	132	334.8
B757	2	6	92	20	110	56	132	144.0
B767	1	39	58	10	83	34	132	227.7
B767	2	7	83	33	152	50	132	158.2
A330-202	1	72	40	10	96	14	132	327.7
A330-202	2	89	68	15	157	45	132	193.1
A330-223	1	250	43	12	82	8	132	306.2
A330-243/1	1	10	39	9	50	26	132	338.5
A330-243/2	1	32	35	12	70	15	132	382.3
A330-243/2	2	8	57	10	72	41	132	233.6
A340-313	1	67	75	16	131	27	132	176.4
A340-313	8	26	74	17	146	54	132	179.0
B777	1	249	38	16	81	9	132	347.4
B777	2	9	59	23	94	21	132	222.8

mentioned previously, the ICAO standard is greater than even the standard deviation about the mean. For another four-engine aircraft, the ARJ100, the ICAO standard lies just above the first standard deviation. In the instances in which the FDR value is greater than the ICAO value, it seems to be occurring with types 2 and 5 fuel takeoff profiles. The ARJ-85 is also a four-engine aircraft but is not showing the same patterns as the others, probably because it is the lightest of this group.

Discussion

The results from this study for a total departure time to 3000 ft, exclusive of the A340-313 and A340-541, are consistent with results from the 2001 AEROCERT report [3]. In that study, only two aircraft, averaged over several airports, had a total departure time greater than the ICAO certification time of 140 s (and less than 150 s). The FDR analysis presented here has mean departure times below 141 s for all aircraft except the A340-313 and A340-541.

Two other studies are available for comparison with the FDR climbout values [12,13]. Both studies used Automated Radar Terminal System (ARTS) data and measured climbout times from 1000 to 3000 ft. One study analyzed times in mode for aircraft operations at six major U.S. airports [12], and the second was undertaken at the McCarren Las Vegas International Airport during the month of July [13]. These two studies plus the FDR data set all show the same results: the ICAO time in mode for climbout is grossly overestimated. The multi-airport study yielded an average of 65 ± 16 s for climbout [12]. The Las Vegas study, conducted in great heat, yielded values from 62 to 93 s [13], again well below the ICAO default of 132 s (2.2 min). The FDR results (Table 7) are consistent with these other studies.

Departure Fuel Burn

Fuel burn is a function of the fuel flow rate and the time in mode. As seen previously, there is considerable variability in fuel flow rates, depending upon the fuel flow type and variability in

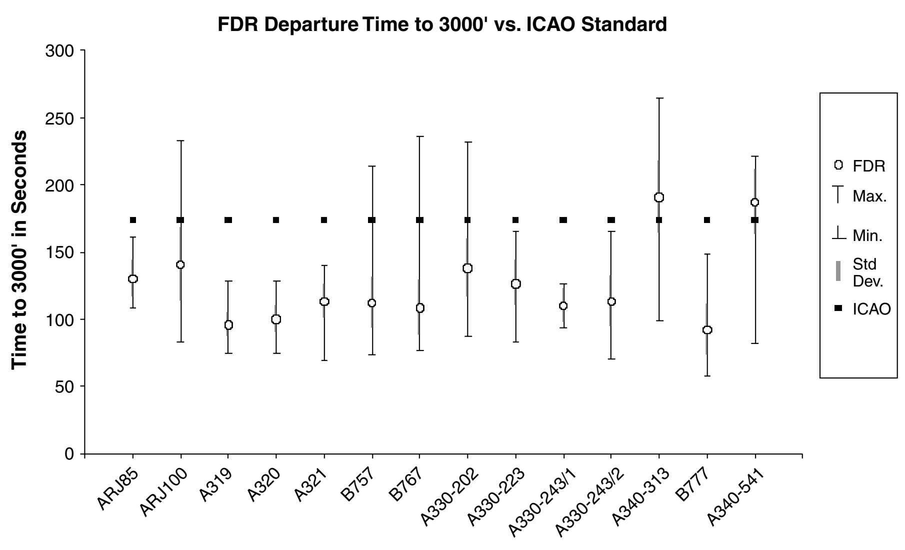

Fig. 5 FDR time from the start of takeoff roll to 3000 ft.

departure time. Although there are cases in which the average fuel flow rate is higher than the ICAO value, this is offset by lower times in mode; consequently, the total departure fuel burn is less than that of the typical ICAO departure with certificated fuel flow rates.

Total departure fuel burn for the aircraft studied is shown in Fig. 6. Only in the case of the four-engine A340-313 is the FDR mean higher than the ICAO value. In all other cases, the ICAO value is higher than the maximum standard deviation and lies outside the standard deviation, but less than the observed maximum for just two aircraft: the ARJ100 and the A330-223.

The general observation that the ICAO predicted fuel burn is greater than the observed fuel burn is probably due to the overall change in fleet from four-engine aircraft, when the ICAO standard was developed, to the present fleet dominated by twin-engine aircraft, which have departure times shorter than the ICAO standard. For safety of flight, all aircraft manufacturers design their multi-engine aircraft with enough thrust to continue climbout after takeoff with one engine inoperative (OEI). The OEI climb criteria mean that two-engine and four-engine aircraft have very different thrust levels available during normal operations.

Generally, under OEI conditions, a two-engine aircraft must have 100% of the safe climb thrust available from the remaining engine; under normal conditions, with both engines operating, a two-engine aircraft has 200% of the safe climb thrust available. Under OEI conditions, a four-engine aircraft must have 100% of the safe climb thrust available from the three remaining engines, and so each engine provides about one-third of the safe climb thrust. Under normal conditions, with all four engines operating, a four-engine aircraft has about 133% of the safe climb thrust available. The actual OEI climbout criteria for aircraft with different numbers of engines are given in Federal Aviation Regulation (FAR) 25.111(c) [14]. Given their larger available climb thrusts, it is therefore expected that the twin-engine aircraft will climb faster than comparable four-engine aircraft; the previous time-in-mode discussion agrees with this expectation. The ICAO times in mode for the LTO cycle were based on data collected in the 1960s at major U.S. airports during high-activity periods [15]. The advances in aircraft development and performance since this time are reflected in the changed times in mode. Therefore, significantly shorter times in departure mean less fuel burn.

Results: Approach

Approach Fuel Flow Rates

Plotted fuel flow rates for approach showed a jagged sawtooth pattern. This is typical of the dive-and-drive method of approach usually used, whereby aircraft fly at a constant flight level until instructed by air traffic controllers to descend to the next flight level, resulting in a drop in fuel flow rates. The pilots then reestablish level flight with an increase in fuel flow before the next descent interval. For this analysis, the fuel flow rate was averaged over the entire approach segment, from 3000 ft AGL to touchdown.

Fuel flow rates were markedly lower than ICAO values for all aircraft except the AR85 and ARJ100, in which the average was close to the ICAO value (Fig. 7). The distribution of the FDR fuel flow values was not symmetrical about the mean, but was rather generally skewed, with the maximum values having greater range from the mean than the minimum values (except for the ARJ100). For three aircraft (A319, B757, and B767), the maximum fuel flow measured equaled the ICAO rate for that aircraft/engine combination in approach, and for two aircraft (A330-202 and A340-313), the maximum exceeded the ICAO rate. For all other aircraft, the ICAO value was greater than any value of fuel flow rate measured (Fig. 7).

Approach Times in Mode

Arrival times from 3000 ft AGL to touchdown are illustrated in Fig. 8. The distribution of approach times was not symmetrical about the mean times, with the exception of the A330-243/1, and was strongly skewed toward the larger approach time in mode. Eleven of the aircraft had mean times in mode that were just slightly greater or lesser than the ICAO value of 4 min (240 s). Three aircraft (B767, A330-202, and A330-243/2) had mean times and first standard deviations greater than the ICAO value.

Approach Total Fuel Burn

The results for total fuel burn during the approach segment of the flights are shown in Fig. 9. In all cases, the quantity of fuel consumed as calculated using ICAO fuel burn rates and time in mode is greater than the mean FDR fuel-consumption values. The distribution of FDR fuel consumption about the mean times is skewed toward the higher fuel-consumption values. However, for 10 of the aircraft, the calculated ICAO fuel burn value lies outside the first standard deviation, and in one case (A330-243/1), it is greater than the highest FDR fuel burn quantity. No variations are seen as in departure for the two- versus four-engine aircraft.

Discussion

In general, approach time-in-mode values are somewhat higher than the ICAO default value. However, fuel flow rates are lower than ICAO values, with the net result that total fuel burn is less than the calculated ICAO value for approach. The FDR results for time in mode for approach are consistent with those from other studies

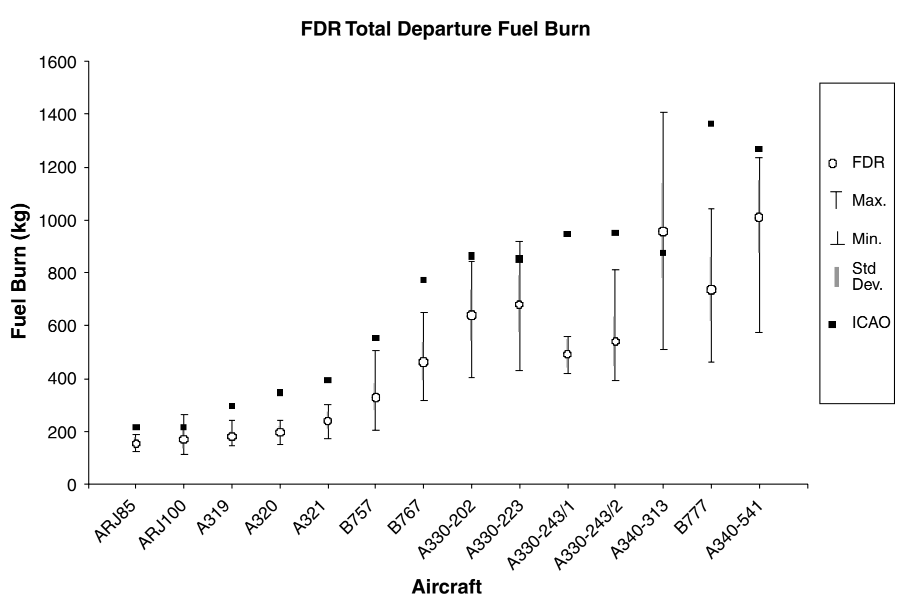

Fig. 6 FDR total departure fuel burn.

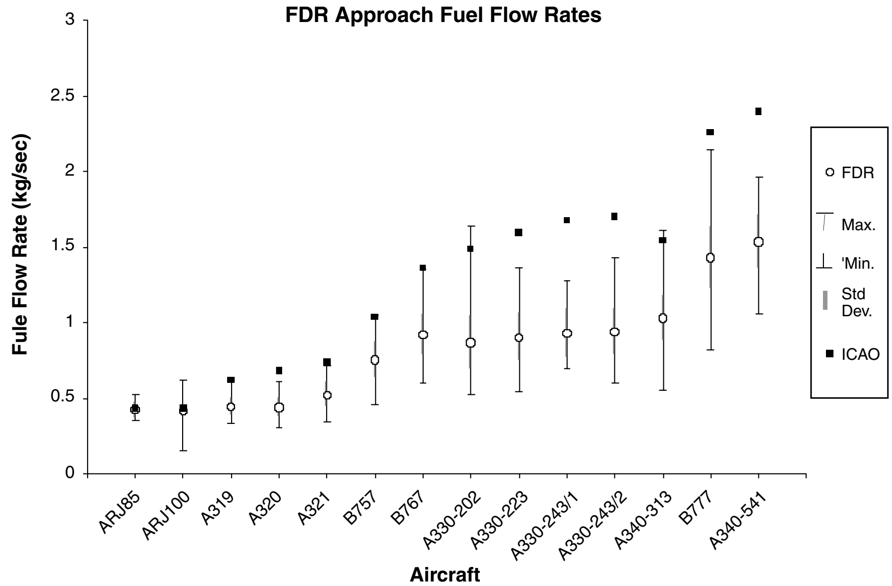

Fig. 7 FDR approach fuel flow rates.

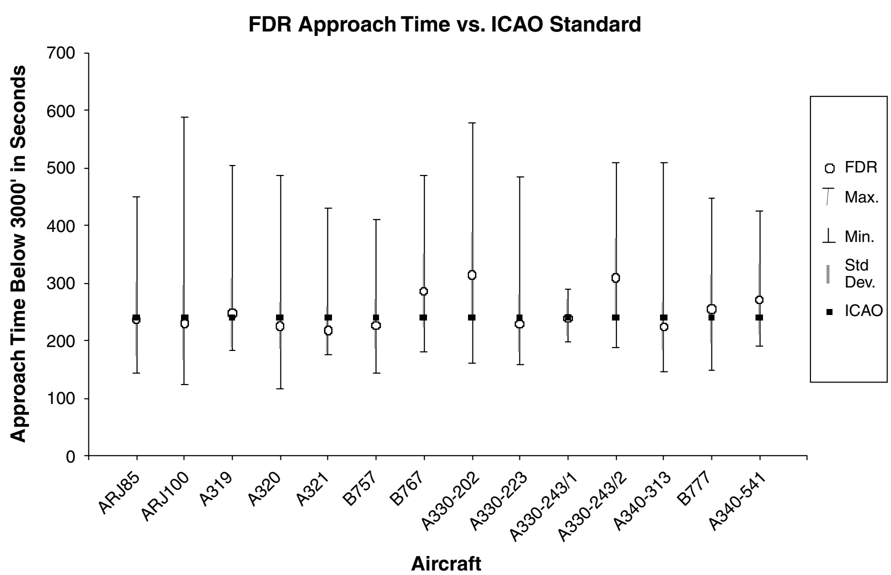

Fig. 8 FDR approach time vs ICAO standard.

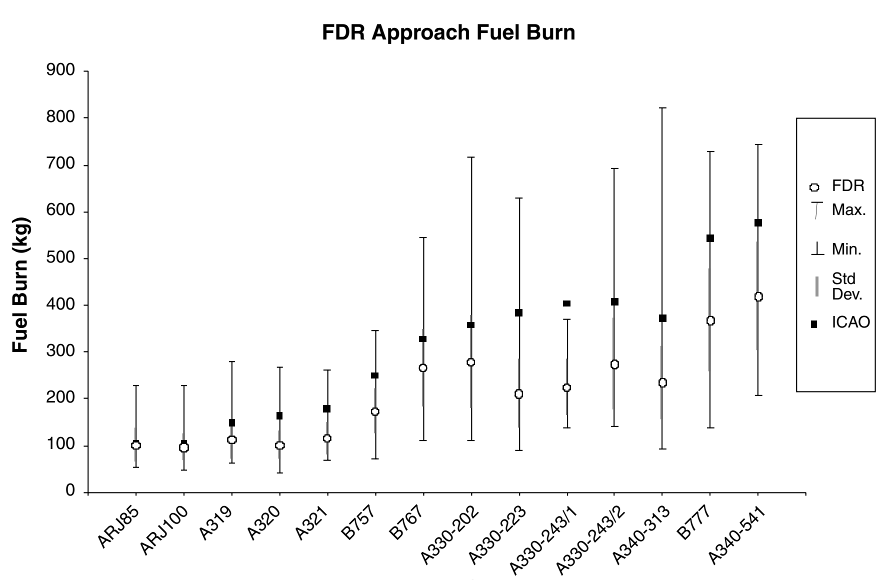

Fig. 9 FDR approach fuel burn.

[3,12]. The AEROCERT analysis had only two aircraft with average approach times at airports below the ICAO default of 240 s, and all other aircraft in the study had average airport approach times greater than the ICAO default, including some values as high as 395 s [3]. The analysis of six major U.S. airports using ARTS data yielded an overall average of $248 + 97$ s [12], just above the ICAO default (240 s). However, the ARTS analysis at the Las Vegas International Airport had average approach values between 1745 and 205 s [13]. Of the 20 aircraft in the McCarren Las Vegas International Airport study, only two were the same airframe as in the FDR data set. No comparative studies were available for fuel flow and total fuel burn during approach.

Conclusions

The acquisition of real-time FDR information provided an opportunity to compare actual fuel flow, times in mode, and total fuel burn under operating conditions with the ICAO standard for aircraft operations during departure and approach. This is important, because the ICAO times in mode are used for some emission inventory work and emission charging schemes. There is a tremendous variety in departure fuel flow patterns, rates of fuel flow, and times in mode. Only 67% of the flights analyzed showed a classic transition from takeoff to climbout with an attendant reduction in fuel flow. The rest of the departures showed an essentially flat-line fuel flow rate, with one exception in the A340-541, which actually showed an increase in fuel flow rate as the departure progressed. Many departure profiles do not have a discernible transition from takeoff to climbout and therefore may not warrant emission calculations based on extant methodologies.

For those flights that did show two definitive modes in departure (takeoff and climbout), there was significant difference in the times in mode from the ICAO standard. Actual takeoff times were significantly higher than the ICAO value, and actual climbout times were much shorter than the ICAO number. On average, the total departure time for aircraft was less than the ICAO value, with the exception of the four-engine A340 aircraft.

Fuel flow rates in departure were highly variable. All aircraft but two models showed takeoffs with fuel flow rate in excess of 100% of the ICAO certification value. Conversely, all aircraft models in departure appeared to have used reduced thrust, with fuel flow rates at an average of 75–80% of certificated values. Long, slow departures showed dips in fuel flow to as low as 30% of maximum.

Fuel flow patterns in approach showed a jagged sawtooth pattern, indicating fluctuation in fuel flow rates during the descent. Average fuel flow rates were lower than the ICAO standard values for approach. Time in mode during approach was slightly longer, on average, than the ICAO value. However, the significantly lower fuel flow rates countered the longer time in mode, and total fuel burn in approach was always lower than the ICAO values.

In general, total fuel burn in both departure and approach was overestimated by the ICAO method. The values for departure determined by ICAO matched favorably to the FDR totals for four-engine aircraft, but grossly overpredicted total fuel burn for the twin-engine aircraft in this study. The results of this study suggest that extant emission inventory models using the ICAO times in mode generate values for quantities of pollutants and greenhouse gases that are excessively higher than what is actually being produced. However, ICAO default times in mode may be appropriate in comparative policy analyses, in which absolute values of fuel burn and emissions are not needed (e.g., for emissions stringency).

Further investigation will compare this data set with fuel burn and emissions produced, as predicted by performance-based models. The present study was limited by a very small sample size of a four-engine aircraft, and the conclusions of this paper need to be tested against data from a broader fleet mix. This work will allow improved prediction of inventories of pollutants and greenhouse gases and refinement of performance-based models, and new policy recommendations may potentially be made for any future emissions trading and charging schemes.

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References

[1] Woodmansey, B. G., and Patterson, Judith, G., "New Methodology for Modeling Annual Aircraft Emissions at Airports," *Journal of Transportation Engineering / American Society of Civil Engineers*, Vol. 120, No. 3, 1994, pp. 339–357. doi:10.1061/(ASCE)0733-947X(1994)120:3(339)

[2] "International Standards and Recommended Practices," *Environmental Protection, Annex 16*, Vol. 2, 2nd ed., International Civil Aviation Organization, Montreal, 1993, p. 55.

[3] Middel, J., "AEROCERT," National Aerospace Laboratory/NLR, Amsterdam, 2001.

[4] "EMEP/CORINAIR Emission Inventory Guidebook—2007," European Environment Agency, TR 16/2007, 2007, http://www.eea.europa.eu/publications/EMEPCORINAIR5 [retrieved 16 Apr. 2009].

[5] *ICAO Engine Emissions Databank* [online database], http://www.caa.co.uk/default.aspx?catid=702&pagetype=90 [retrieved 11 Apr. 2009].

[6] Klee, U. (ed.), *JP Airline-Fleets International 2006/07*, 40th ed., Bucher & Co., Zurich, Switzerland, 2006.

[7] MATLAB, Software Package, Ver. 7, Release 14, The MathWorks, Inc., Natick, MA, 2004.

[8] *A340 Flight Manual*, Airbus Customer Services Directorate, Blagnac, France, May 2003, pp. 1–17.

[9] *The Aircraft Gas Turbine Engine and Its Operation*, McGraw–Hill, New York, 1988.

[10] Curran, R., "Correction to Engine Emission Data Resulting from Engine Deterioration," QinetiQ, Ltd., Rept. QINETIQ/05/01726, Farnborough, England, U.K., 2006.

[11] Tegtmeier, L. A., "United, Southwest Sign for Engine Washing," *Aviation Week & Space Technology*, June 2008.

[12] Rice, C. C., "Validation of Approach and ClimbOut times in Mode for Aircraft Emissions Computation," *Transportation Research Record*, Vol. 1850, 2003, pp. 79–82. doi:10.3141/1850-09

[13] Hall, C. T., Thrasher, T. G., and Draper, J. A., "A Validation of Aircraft Times in Mode in the Emissions and Dispersion Modeling System (EDMS) Version 4.2," 98th Annual Conference and Exhibition, Air and Waste Management Association Paper 514, 2005.

[14] *U.S. Code of Federal Regulations, Title 14, Aeronautics and Space*, Part 25.111(c), U.S. Government Printing Office, Washington, D.C., 2007.

[15] "Control of Air Pollution from Aircraft and Aircraft Engines," *Federal Register*, Vol. 37, No. 239, Dec. 1972, pp. 26488–26500.