Technical Support Report

Aircraft Emission Factors

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Abstract

Modal emission factors have been calculated for a number of gas turbine and piston aircraft engines. Emission factors per aircraft per landing takeoff cycle have been calculated for representative aircraft-engine combinations. This group includes commercial jet transports, business jets, turboprops and general aviation piston aircraft.

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Introduction

In order to perform useful air quality analysis it is necessary to have the most accurate emission factor data available. The purpose of this report is to provide updated aircraft engine emission factors and a sample of the calculation methodology used in obtaining these numbers.

Two types of data will be presented for each engine studied, modal emission factors (pounds pollutant per hour at each operating mode) and emission factors per aircraft landing-takeoff cycle (total pounds pollutant per LTO).

Both of these types of data are based on the landing and takeoff cycle. A landing-takeoff (LTO) cycle includes all normal operational modes performed by an aircraft between the time it descends through an altitude of 3,500 feet (1,100 meters) on its approach and the time to the 3,500 foot (1,100 meters) altitude after takeoff. The LTO cycle incorporates the ground operations of idle, taxi, landing run, and takeoff run and the flight operations of takeoff and climbout to 3,500 feet (1,100 meters) and approach from 3,500 feet (1,100 meters) to touchdown. Each class of aircraft has its own typical LTO cycle. In order to determine emissions, the LTO cycle is separated into five distinct modes (1) taxi-idle-out, (2) takeoff, (3) climbout, (4) approach and landing, and (5) taxi-idle-in. Each of these modes has its share of time in the LTO. Table 1 shows typical operating time in each mode for various types of aircraft classes during periods of heavy activity at a large metropolitan airport.

Modal Emission Factors

In Table 2 a set of modal emission factors by engine type are given for carbon monoxide, total hydrocarbons and nitrogen oxides along with the fuel flow rate per engine for each LTO mode. With this data and knowledge of the time in mode, it is possible to construct any LTO cycle or mode and calculate a more accurate estimate of emissions for the situation that exists at a specific airport. This capability is especially important for estimating emissions during the taxi-idle mode when large amounts of carbon monoxide and hydrocarbons are emitted. At smaller commercial airports the taxi-idle time will be less than at the larger, more congested airports.

See Appendix A for sample modal emission factor calcualtions.

Emission Factor Per Aircraft Per Landing Takeoff Cycle

In Table 3 a set of emission factors by aircraft-engine combinations are given for carbon monoxide, total hydrocarbons, and nitrogen oxides. The aircraft-engine combination were choosen by selecting a typical aircraft for which engine emission data was available. The emission factor presented represents the total pounds of pollutant emitted by each aircraft per landing-takeoff cycle. Thus, for multiengine aircraft the emission factors include the sum of pollutants from each engine.

See Appendix B for sample calculations.

TABLE 2 - MODAL EMISSION FACTORS

Gas Turbines / Engine and Mode	Fuel Rate		Carbon Monoxide		Hydrocarbons		Nitrogen Oxides (NO_x as NO_2)	
	LB/HR	KG/HR	LB/HR	KG/HR	LB/HR	KG/HR	LB/HR	KG/HR
General Electric CF700-2D								
Idle	460	208.7	71.30	32.34	8.28	3.76	.41	.186
Takeoff	2607	1182	57.35	26.01	.26	.118	14.60	6.62
Climbout	2322	1053	58.05	26.33	.23	.104	9.98	4.53
Approach	919	416.9	56.98	25.85	1.29	.585	1.65	.748
General Electric CF6-6D								
Idle	1063	482.2	65.06	29.51	21.79	9.88	4.88	2.21
Takeoff	13750	6237	8.25	3.74	8.25	3.74	467.5	212.1
Climbout	11329	5139	6.80	3.08	6.80	3.08	309.2	140.2
Approach	3864	1753	23.18	10.51	6.96	3.16	41.54	18.84
General Electric CF6-50C								
Idle	1206	547	88.04	39.93	36.18	16.41	3.02	1.37
Takeoff	18900	8573	.38	.172	.19	.086	670.95	304.3
Climbout	15622	7104	4.70	2.13	.16	.073	462.0	209.6
Approach	5280	2395	22.70	10.30	.05	.023	52.8	23.95
Pratt & Whitney JT3D-7								
Idle	1013	459.5	140.8	63.87	124.6	56.52	2.23	1.01
Takeoff	9956	4516	8.96	4.06	4.98	2.26	126.4	57.34
Climbout	8188	3714	15.56	7.06	3.28	1.49	78.6	35.65
Approach	3084	1399	60.14	27.28	6.48	2.94	16.35	7.42

Table 2 - Modal Emission Factors (gas turbines)

Engine and Mode	Fuel Rate		Carbon Monoxide		Hydrocarbons		Nitrogen Oxides (NO_x as NO_2)	
	LB/HR	KG/HR	LB/HR	KG/HR	LB/HR	KG/HR	LB/HR	KG/HR
Pratt & Whitney JT8D-17								
Idle	1150	521.6	39.10	17.74	10.10	4.58	3.91	1.77
Takeoff	9980	4527	6.99	3.17	.50	.227	202.6	91.90
Climbout	7910	3588	7.91	3.59	.40	.181	123.4	55.97
Approach	2810	1275	20.23	9.18	1.41	.640	19.39	8.80
Pratt & Whitney JT9D-7								
Idle	1849	838.7	142.4	64.59	55.10	24.99	5.73	2.60
Takeoff	16142	7322	3.23	1.47	.81	.367	474.6	215.3
Climbout	13193	5984	6.60	2.99	1.32	.599	282.3	128.0
Approach	4648	2108	44.62	20.24	4.65	2.11	36.25	16.44
Pratt & Whitney JT9D-70								
Idle	1800	816.5	61.20	27.76	12.24	[illegible].55	5.76	2.61
Takeoff	19380	8791	3.88	1.76	2.91	1.32	600.8	272.5
Climbout	15980	7248	4.79	2.17	2.40	1.09	386.7	175.4
Approach	5850	2654	7.61	3.45	2.63	1.19	47.39	21.50
Rolls Royce Spey 555								
Idle	755	342.5	36.77	16.68	9.51	4.31	.83	.376
Takeoff	5516	2502	28.13	12.76	14.89	6.75	80.53	36.53
Climbout	4501	2041	38.71	17.56	16.20	7.35	50.41	22.87
Approach	1655	750.7	41.71	18.92	8.28	3.76	6.95	3.15

Table 2 - Modal Emission Factors (gas turbines)

Engine and Mode	Fuel Rate		Carbon Monoxide		Hydrocarbons		Nitrogen Oxides (NO_x as NO_2)	
	LB/HR	KG/HR	LB/HR	LB/HR	LB/HR	KG/HR	LB/HR	KG/HR
Pratt & Whitney Aircraft of Canada JT15D-1								
Idle	215	97.52	19.46	8.83	7.48	3.39	.54	.245
Takeoff	1405	637.3	1.41	.640	0	0	14.19	6.44
Climbout	1247	565.6	1.25	.567	0	0	11.35	5.15
Approac	481	218.2	11.45	5.19	1.59	.721	2.45	1.11
Pratt & Whitney Aircraft of Canada PT6A-27								
Idle	115	52.16	7.36	3.34	5.77	2.62	.28	.127
Takeoff	425	192.8	.43	.195	0	0	3.32	1.51
Climbout	400	181.4	48	.218	0	0	2.80	1.27
Approach	215	97.52	4.95	2.24	.47	.213	1.80	.816
Pratt & Whitney Aircraft of Canada PT6A-41								
Idle	147	66.68	16.95	7.69	14.94	6.78	.29	.132
Takeoff	510	231.3	2.60	1.18	.89	.404	4.07	1.85
Climbout	473	214.6	3.07	1.39	.96	.435	3.58	1.62
Approach	273	123.8	9.50	4.31	6.20	2.81	1.27	.576
General Motors Allison 250B17B								
Idle	63	28.58	6.13	2.78	1.27	.576	.09	.041
Takeoff	265	120.2	2.07	.939	.07	.032	1.75	.794
Climbout	245	111.1	2.21	1.00	.09	.041	1.46	.662
Approach	85	38.56	4.13	1.87	.44	.200	.19	.086
General Motors Allison 501D22A								
Idle	610	276.7	26.60	12.07	10.74	4.87	2.15	.975
Takeoff	2376	1078	4.85	2.20	.67	.304	21.10	9.57
Climbout	2198	997	4.53	2.05	1.96	.889	20.27	9.19
Approach	1140	517.1	5.81	2.64	2.23	1.01	8.54	3.87

Table 2 - Modal Emission Factors (gas turbines)

General Aviation Piston	Fuel Rate		Carbon Monoxide		Hydrocarbons		Nitrogen Oxides (NO_x as NO_2)	
Engine and Mode	LB/HR	KG/HR	LB/HR	KG/HR	LB/HR	KG/HR	LB/HR	KG/HR
Avco/Lycoming IO-320-D1AD								
Taxi-Idle	7.84	3.56	4.86	2.20	.283	.128	.009	.0041
Takeoff	91.67	41.57	109.3	49.55	1.047	.475	.167	.0756
Climbout	61.42	27.85	54.55	24.74	.588	.267	.344	.156
Approach	37.67	17.08	35.57	16.13	.460	.208	.128	.058
Avco/Lycoming IO-360-B								
Taxi-Idle	8.09	3.68	7.26	3.29	.398	.180	.0094	.0042
Takeoff	103.0	46.7	123.5	56.0	1.03	.469	.205	.093
Climbout	71.7	32.5	70.5	32.0	.585	.265	.329	.149
Approach	36.6	16.6	25.3	11.5	.355	.161	.372	.169
Avco/Lycoming TIO-540-J2B2								
Taxi-Idle	25.06	11.36	32.42	14.70	1.706	.774	.0097	.0044
Takeoff	259.7	117.8	374.5	169.8	3.21	1.46	.094	.043
Climbout	204.5	92.7	300.8	136.4	3.40	1.54	.0481	.0218
Approach	99.4	45.1	125.4	56.9	1.33	.604	.138	.0623
Taxi-Idle								
Takeoff								
Climbout								
Approach								

Table 2 - Modal Emission Factors (general aviation piston)

Table 3 - EMISSION FACTORS PER AIRCRAFT PER L.T.O. CYCLE

Representative Aircraft Commercial Jets	Engine Model and Manufacturer	Engines Per Aircraft	Emission Factors Per Aircraft Per Landing-Takeoff Cycle					
			Carbon Monoxide		Hydrocarbons		Nitrogen Oxides	
			LB	KG	LB	KG	LB	KG
Boeing 747-200B	Pratt & Whitney JT9D-7	4	259.64	117.76	96.92	43.96	83.24	37.76
Boeing 747-200B	Pratt & Whitney JT9D-70	4	108.92	49.40	22.40	10.16	107.48	48.76
McDonnell Douglas DC10-30	General Electric CF6-50C	3	116.88	53.01	47.10	21.36	49.59	22.17
Boeing 707-320B	Pratt & Whitney JT3D-7	4	262.64	119.12	218.24	99.00	25.68	11.64
Boeing 727-200	Pratt and Whitney JT8D-17	3	55.95	25.38	13.44	6.09	29.64	13.44
Boeing 737-200	Pratt & Whitney JT8D-17	2	37.30	16.92	8.96	4.06	19.76	8.96
McDonnell Douglas DC7 Series 50	Pratt & Whitney JT8D-17	2	37.30	16.92	8.96	4.06	19.76	8.96
McDonnell Douglas DC8	Pratt & Whitney JT3D-7	4	262.64	119.12	218.24	99.00	25.68	11.64

Table 3a - Commercial Jets

Representative Aircraft Business Jets	Engine Model and Manufacturer	Engines Per Aircraft	Emission Factors Per Aircraft Per Landing-Takeoff Cycle					
			Carbon Monoxide		Hydrocarbons		Nitrogen Oxides	
			LB	KG	LB	KG	LB	KG
Cessna Citation	Pratt & Whitney JT15D-1	2	9.10	4.41	3.32	1.51	.742	.336
Learjet 24D	General Electric CJ610-6	2	41.22	18.70	4.14	1.88	.588	.266
Learjet 35, 36	Garrett AiResearch TFE 731-2	2	5.39	2.44	1.84	.834	1.22	.553
Rockwell International Sabre 75A	General Electric GE CF700	2	35.67	16.18	3.66	1.66	.626	.284

Table 3b - Business Jets

Representative Aircraft Business Turboprops	Engine Model and Manufacturer	Engines Per Aircraft	Emission Factors Per Aircraft Per Landing-Takeoff Cycle					
			Carbon Monoxide		Hydrocarbons		Nitrogen Oxides	
			LB	KG	LB	KG	LB	KG
Beech B99 Airliner	United Aircraft of Canada PTGA-27	2	7.16	3.25	5.08	2.30	.687	.312
deHavilland Twin Otter	United Aircraft of Canada PTGA-27	2	7.16	3.25	5.08	2.30	.687	.312
Shorts Skyvan-3	Garrett TPE 331-2	2	6.44	2.92	8.40	3.81	.883	.400
Swearingen Merlin IIIA	Garrett TPE 331-3	2	6.28	2.85	7.71	3.50	1.15	.522

Table 3d - Business Turboprops

Appendix A

Sample Modal Emission Factors Calculation

1) Gas Turbines

The data used in calculating gas turbine modal emission factors were taken from Reference 1. Referring to Reference 1, we have the following data for the Pratt & Whitney JT9D-7 gas turbine.

Mode	Fuel Flow (lbs/hr)	Emission Index $\left(\frac{\text{lbs. pollutant}}{\text{1000 lbs. fuel}}\right)$		
		HC	CO	NOx
Idle	1849	29.8	77.0	3.1
Approach	4648	1.0	9.6	7.8
Climbout	13193	0.1	0.5	21.4
Takeoff	16142	0.05	0.2	29.4

To obtain the modal emission rates perform the following calculation.

Emission Index x Fuel Flow = Modal Emission Rate

For the idle mode the above methods give the following values for unburned hydrocarbons.

$$29.8\left(\frac{\text{lbs. HC}}{\text{1000 lbs. fuel}}\right) \times 1849\left(\frac{\text{lbs. fuel}}{\text{hr.}}\right) = 55.1\left(\frac{\text{lbs. HC}}{\text{hr}}\right)$$

Similar methods are used for the other modes and pollutants.

Appendix B

Sample Calculations for Emission Factors per Aircraft per Landing Takeoff Cycle

To calculate emission factors per aircraft per landing takeoff cycle take a representative aircraft-engine combination, use the appropriate modal emission factors from table 2 and multiply by a typical time in mode from table 1.

As an example use the Cessna Citation powered by 2 Pratt & Whitney JT15D-1 gas turbine engines. This is a typical in-use business jet. Table 1 gaves the following time in modes for this type of aircraft.

Mode	Time (min)
Taxi-idle	13.0
Takeoff	0.40
Climbout	0.50
Approach	1.60

From Table 2 take the following data.

Mode	CO (#/hr)	HC (#/hr)	NOx (#/hr)
Taxi-idle	19.46	7.48	0.54
Takeoff	1.41	0	14.19
Climbout	1.25	0	11.35
Approach	11.45	1.59	2.45

Using this data perform the following calculation (using CO as an example).

$$(19.46\ \#/\text{hr})\left(\frac{13\ \text{min}}{60\ \text{min/hr}}\right) + (1.41\ \#/\text{hr})\left(\frac{.40\ \text{min}}{60\ \text{min/hr}}\right) + (1.25\ \#/\text{hr})\left(\frac{.50\ \text{min}}{60\ \text{min/hr}}\right)$$

$$+ (11.45\ \#/\text{hr})\left(\frac{1.60\ \text{min}}{60\ \text{min/hr}}\right) = 4.54 \text{ lbs. CO per aircraft engine per landing takeoff cycle}$$

This aircraft uses two engine, therefore;

$$2 \times 4.54 \text{ lbs. CO} = 9.08 \text{ lbs. CO}$$

The number is the total number of pounds of carbon monoxide emitted by this aircraft for the landing takeoff cycle used. Similar calculations are performed for HC and NOx.

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