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Fuel Flow Rate and Duration of General Aviation Landing and Takeoff Cycle

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General aviation delivers transport of critical cargo and passengers, and offers the joy of recreational flying to people. The FAA reports that the US general aviation activities reached almost 23 million flight hours in 2013; however, along with these activities there is a considerable amount of gaseous and particulate matter exhaust emissions. One set of parameters required to precisely estimate the mass of gaseous and particulate matter exhaust emissions is the landing and take-off (LTO) cycle characteristics. This paper develops a model to identify each phase of flight in the LTO cycle for general aviation operations to be used in exhaust emissions analyses. The definitions of each phase of flight used for exhaust emissions purposes are compared to the definitions for general use and for use in safety analysis. Using an emission analysis viewpoint, the duration of each phase of flight and the average fuel flow rate in each phase of flight are estimated from flight data. These durations and fuel flow rates are necessary for estimating the mass of specific gaseous and particulate matter emissions using the emissions indices available in the International Civil Aviation Organization Aircraft Engine Emissions Databank. The current parameters available in the system tables in the Emissions and Dispersion Modeling System (EDMS) were developed prior to the availability of technologically advanced aircraft in the fixed wing, reciprocating engine small aircraft such as the Cirrus SR-20. The LTO model is analyzed using a sample of historical flight data of the Cirrus SR-20 fleet of Purdue University. When compared to EPA, ICAO and FOCA durations, the data from the SR-20s is shown to be different using a statistical significance of 0.05.

Nomenclature

AEDT V 2b = Aviation Environmental Design Tool Version 2b, replaces EDMS
AGL = Altitude Above Ground Level
DUR = Duration of phase in minutes
EI = Emission Indices for mass of specific emissions in kg-emission/kg-fuel
EDMS = Emissions and Dispersion Modeling System

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FFR = Fuel Flow Rate
FOCA = Federal Office of Civil Aviation, Switzerland
FAA = Federal Aviation Administration, United States of America
GndSpd = Ground Speed
GA = General Aviation
GAMA = General Aviation Manufacturers Association
ICAO = International Civil Aviation Organization, a United Nations specialized agency
IATA = International Air Transportation Association, a transport category trade group
KIAS = Indicated Air Speed in Nautical Miles Per Hour
RPM = Revolutions Per Minute

I. Introduction

Aviation plays an important role in global economic activity and in peoples' daily lives. Worldwide, people benefit greatly from the ability to travel for business or pleasure and move freight over a long distance in a short period of time. Air transport carries 35% of all good by value, and supports 3.5% of global GDP[1]. International Civil Aviation Organization (ICAO) estimated that in 2014 the total number of passengers carried on scheduled flights reached 3.3 billion, which is almost 1.5 times the level in 2005; the air freight reached 50.4 million metric tons with 3.9% of annual increase rate[2]. Since 1977, global air traffic has doubled in size every 15 years, and ICAO forecasts that between 2013 and 2030 the numbers will double again. In other words, the number of airline passengers are expected to grow to around six billion by 2030; air cargo traffic is also expected to follow a similar upward trend to reach 100 million metric tons by 2030[3].

Air transport has tremendously elevated the quality of life with its revolutionary efficiency and largely shrunk the borders of the world[4]. However, aviation also generates environmental impacts. Early in 1983, the Committee on Aviation Environmental Protection (CAEP) was established under ICAO to study and develop proposals to minimize aviation's effects on the environment. Improving the environmental performance of aviation is a challenge for ICAO to address. Confronted with the environmental issues, ICAO adopted three major environmental goals, to:

a. Limit or reduce the number of people affected by significant aircraft noise;
b. Limit or reduce the impact of aviation emissions on local air quality; and
c. Limit or reduce the impact of aviation greenhouse gas emission on the global climate[1].

The International Air Transport Association (IATA) also adopted a set of similar targets to mitigate the environmental impacts of civil air transport on climate change, aircraft noise, and local air quality[5]. The European Commission proposed to include aviation in the European Union emissions trading scheme (ETS), which is in the line with ICAO's resolution (A35-5) in incorporating international aviation into existing emissions trading schemes[6]. Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA) and the U.S. Environmental Protection Agency (EPA) also have been working to elucidate and address the environmental issues caused by aircraft engines.

In order to control the gaseous and particulate matter emissions from air transport, ICAO proposed the standards for emissions certification of aircraft turbine engines which currently cover unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx) and smoke (SN). The standards are concerned with local air quality in the vicinity of airport and focuses are the effects of emissions released below the mixing height altitude, which is generally 3000 feet (915 meters) above the ground level (AGL)[21]. The engine emissions certification process is based on the Landing and Take-off (LTO) cycle, and in the US, this data is reported under Title 14 CFR Part 34. The Emissions Index (EI) data are then added to the ICAO engine data bank.

To conduct an exhaust emission study for an airport, exhaust emissions are estimated for each phase of the LTO cycle of each aircraft type by using the emission indices for the aircraft's specific engine at each power setting or mode of operation, the fuel flow rate at each mode of operation, and the time spent in each mode. The total gross emissions for an airport could be estimated by using the number of aircraft LTOs during a time period shown as Equation (1)[7].

$$\textit{Total Emissions of pollutant } j = \Sigma(EI_{i,j} * FFR_i * DUR_i * LTO_i) \qquad (1)$$

where $EI_{i,j}$ = aircraft engine emission index for a specific pollutant of j in the phase of flight of i (kg-exhaust chemical/ kg-fuel burned), FFR_i = the average fuel flow rate in the phase of flight of i (kg-fuel/s), i = phase of flight (taxi/idle, takeoff, climb-out, approach), DUR_i = the duration of the phase of flight of i (s), LTO_i = the number of the phase of flight of i per aircraft type during a time period, and Σ = the sum of each phase of flight in LTO cycle.

Following ICAO's international standards and recommended practices on aircraft engine emissions measuring procedure, the US EPA added the Emissions and Dispersion Modeling System (EDMS) into the Guideline on Air Quality Models in 1993. The EDMS was developed in the mid-1980s as a complex software model used to evaluate the air quality impacts of proposed airport development projects, and it has been replaced by the Aviation Environmental Design Tool, Version 2b (AEDT), which is more comprehensive that includes the phase of cruise and noise consideration[8]. Also, to assist with environmental impact assessments, EUROCONTROL, supported by the EU and the European Aviation Safety Agency (EASA), has developed a series of environmental modeling tools and air traffic movement database, including the Advanced Emissions Model (AEM), Airport Local Air Quality Studies (ALAQS) model[9, 10].

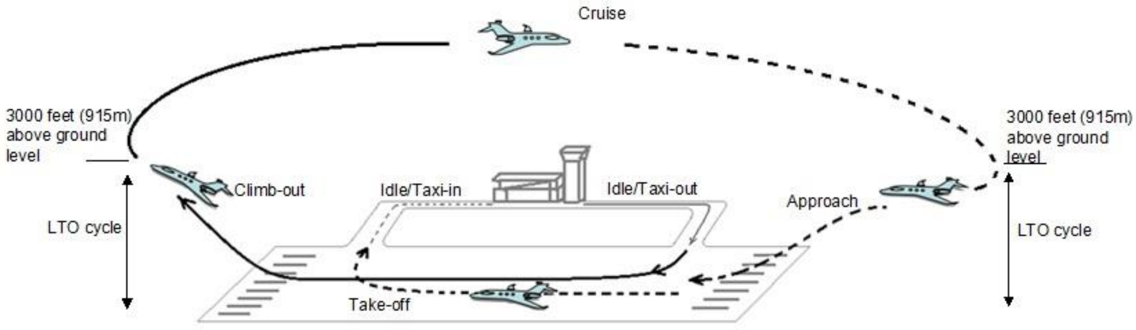


Figure 1. ICAO reference Landing and Takeoff cycle. (Adapted from ICAO LTO cycle)

Due to the increasing amount of residential development surrounding airports and continued growth of General Aviation (GA) activities, GA emissions share a responsibility on environmental impacts on local air quality. By 2014, there were more than 362,000 general aviation aircraft worldwide, of which over 199,000 aircraft are based in the United States flying almost 23 million flight hours annually across more than 5000 U.S. public airports[11]. In Europe, General aviation fleet reaches 10,300 aircraft accessing over 4200 airports[11]. In 2005, the FAA proposed a methodology to estimate the GA and air taxi aircraft exhaust emissions based on the LTO cycle[4]. However, the aircraft in the GA fleets have a variety of aircraft engines, such as reciprocating, turbofan, turboprop, and turboshaft.

Piston-engine aircraft have different flying performance characteristics than turbine-engine aircraft, and therefore not all GA aircraft operate in a manner similar to the standard LTO turbine cycle shown in table 1. By 2013, piston-engine aircraft occupy almost 69% of the gross number of active GA aircraft[12]. Considering the characteristics of GA operations, we developed a comparison of LTO phase of flight definitions shown in table2.

Table 1. Thrust settings and time-in-mode of ICAO reference LTO cycle[7]

Operating Mode	Thrust setting(% of maximum sea level static thrust)	Time-in-Mode(min)
Take-off	100%	0.7
Climb-out	85%	2.2
Approach-landing	30%	4.0
Taxi/idle	7%	26.0

Table 2. Definition of Phases of Flight

Phases of Flight	ICAO Definition in ICAO Annex.16 Volume II[1](specific for estimating emissions)	NTSB Definition[2]	ICAO General Definition[3]
Afterburning	A mode of engine operation wherein a combustion system fed (in whole or part) by vitiated air is used. Phase is defined for emissions assessment	No	No
Standing	No	Prior to pushback or taxi, or after arrival, at the gate, ramp, or parking area, while the aircraft is stationary	Any time before taxi or after arrival while the aircraft is stationary
Pushback/Towing	No	Aircraft is moving in the gate, ramp, or parking area, assisted by a tow vehicle	Same as NTSB definition
Taxi/ground idle	The operating phase involving taxi and idle between the initial starting of the propulsion engine(s) and the initiation of the take-off roll and between the time of runway turn-off and final shutdown of all propulsion engine(s)	The aircraft is moving on the aerodrome surface under its own power prior to takeoff or after landing	Same as NTSB definition
Take-off	The operating phase defined by the time during which the engine is operated at the rated thrust	From the application of takeoff power, through rotation and to an altitude of 35 feet above runway elevation	Same as NTSB definition
	The operating phase defined	From the end of the Takeoff subphase to the first prescribed power	Any time the aircraft

Climb	by the time during which the engine is operated in the climb operating mode	eduction, or until reaching 1,000 feet above runway elevation or the VFR pattern, whichever comes first	has a positive rate of climb for an extended period of time
En route	No	From completion of Initial Climb through cruise altitude and completion of controlled descent to the Initial Approach Fix (IFR); From completion of Initial Climb through cruise and controlled descent to the VFR pattern altitude or 1,000 feet above runway elevation, whichever comes first (VFR)	The time period of following the initial climb during which the aircraft is in level flight
Maneuvering	No	Low altitude/aerobatic flight operations	Same as NTSB definition
Approach	The operating phase defined by the time during which the engine is operated in the approach operating mode	From the Initial Approach Fix (IAF) to the beginning of the landing flare (IFR); From the point of VFR pattern entry, or 1,000 feet above the runway elevation, to the beginning of the landing flare (VFR)	Same as NTSB definition
Landing		From the beginning of the landing flare until aircraft exits the landing runway, comes to a stop on the runway, or when power is applied for takeoff in the case of a touch-and-go landing	Same as NTSB definition
Emergency Descent	No	A descent during any airborne phase in response to a perceived emergency situation;	Same as NTSB definition
Uncontrolled Descent	No	A descent during any airborne phase in which the aircraft does not sustain controlled flight	Same as NTSB definition

Note: 1) ICAO Environmental Protection Annex.16 Volume II[7]. 2) NTSB Phase of Flight: Definition and Usage Note[13]. 3) ICAO ADREP 2000 Taxonomy: Event Phases (ECCAIRS 4.2.6)[14].

Early in 1985, US EPA proposed the default time-in-modes of LTO for various aircraft categories according to aircraft data for the purpose of emission inventory preparation[15]. Based on the ICAO reference LTO cycle proposed in 1993, Swiss Federal Office of Civil Aviation (FOCA) measured the emissions performance of a wide range of existing aircraft piston engines which didn’t have ICAO emissions certification based on LTO cycle at the time of 2007[16]. FOCA considered the fact that the piston-engine aircraft are intensely used for training and school flights, where traffic pattern flight circling around the airport happens a lot, as well as other variables of aircraft type, airport location, and airfield size. FOCA suggested new times in mode for the LTO cycle to compare piston engine emissions in the LTO band of 3000ft AGL to other types of engines (see Table 3). FOCA also suggested to calculate the climb-out segment of the LTO with take-off emission factors and take-off fuel flow because majority of engines below 200 HP are operated at full power when climbing out up to 3000ft AGL[16]. Researchers on aviation gaseous and particulate emissions also realize that the duration of aircraft activities in different modes of the LTO cycle depends on the airport layout and number of aircraft movements, and the use of real world time-in-mode data was crucial for a realistic emissions inventory of the airport[17].

Table 3. LTO times in mode from ICAO, US EPA, and Swiss FOCA

Mode	**[1]ICAO Reference Duration in Mode (Minutes)**	**[2]US EPA Reference Duration in Mode for Piston Engine (Minutes)**	**[3]FOCA Reference Duration in Mode for Piston Engine (Minutes)**
Take-off	0.7	0.3	0.3
Climb-out	2.2	5.0	5.0
Cruise	-	-	-
Approach	4.0	6.0	6.0
Taxi/Idle	26.0	16.0	16.0

Note: 1) ICAO Environmental Protection Annex.16 Volume II[7]. 2) US EPA, Compilation of Air Pollutant Emission Factors Volume II[15]. 3) Swiss FOCA Summary Report of Aircraft Piston Engine Emissions[16].

In 2014, Katsaduros et al. estimated and compared emissions at Purdue University Airport (KLAF) using the Emissions & Dispersion Modeling System (EDMS) with the reference in ICAO Annex 16 Volume II and their customized inputs, and explored emissions modeling for a General Aviation airports using airport-specific LTO cycle data[18]. Considering the accuracy of general aviation LTO data available in EDMS, Varney et al. (2015) analyzed flight data from aircraft at a specific airport with MATLAB, and outputted the fuel flow rate and time in modes for each phase of the LTO cycle[19]. From the perspective of General Aviation safety, Goblet V et al. (2015) presented initial work on automatically identifying phases of flight from flight data in GA using the NTSB definition to assist to identify safety events[20].

This paper presents research on developing duration and fuel flow rates for each phase in the LTO cycle that could be used in estimating the gaseous and particulate emissions at General Aviation airports. Unlike commercial flight operations which are scheduled with clear phases of flight, including taxi, take-off, climb-out, cruise, descent, approach and landing; most GA operations are not based on a regular schedule and prescribed phases of flight. Therefore, the phases of flight may be more difficult to identify in flight data because of diverse GA flight missions. The standard LTO cycle proposed by ICAO may not be applicable for GA operations since it mainly targets turbine aircraft in commercial flight. Estimating the mass of exhaust emissions for fixed wing, reciprocating engine GA aircraft operations by using the ICAO standard LTO cycle for turbines may result in errors.

In order to improve the accuracy of estimating GA emissions in airport area, the research questions posed by this paper are:

1) What is the operational definition of LTO phases for GA reciprocating engine aircraft for use in exhaust emission modeling?
2) What are the estimated fuel flow rate and duration for each phase of flight at a specific GA airport?
3) Are these estimators the same or different from those used in exhaust emission modeling by ICAO, US EPA, and Swiss FOCA?

To answer these questions, this paper presents exploration on solutions to above problems with following methods:

1) Analyze the definitions of LTO phases currently used by ICAO, US EPA, and Swiss FOCA.
2) Analyze the characteristics of flight profile and operational characteristics of reciprocating engine GA aircraft of the Cirrus SR-20 fleet of Purdue University.
3) Develop a model to identify the phases of flight in LTO cycle for GA reciprocating engine aircraft.
4) Test the model using the flight data from Garmin G1000 avionic system on board of Cirrus SR-20 of Purdue University.
5) Estimate the duration and the average fuel flow rate in each phase of flight identified by the model.
6) Analyze the statistical characteristics of the outputs of DUR and FFR, and compare the outputs of DUR and FFR to the references of ICAO, US EPA, and Swiss FOCA

II. Model of Identifying the Phases of Flight in General Aviation LTO

A. Data Collection

The historical flight data recorded by on-board Garmin G1000 avionics system from the Cirrus SR-20 fleet of Purdue University were collected. Garmin G1000 recorded the real-time aircraft activities data with 66 parameters, including flight date, time, aircraft location in terms of coordinates, altitude, engine revolution per minute, indicated air speed, ground speed, vertical speed, pitch angle and other standard parameters for the G1000. The flight missions selected were cross-country flights and local traffic pattern flights with flight durations from 77 minutes to 198 minutes. All aircraft in this sample are based in West Lafayette, IN.

B. Modeling the Phases of Flight

Unlike commercial flights which have clear and regular phases of flight, piston-engine GA aircraft operate differently in terms of flight performance, pilot controlling, and engine mode in each phase of flight. Figure 2 demonstrates the aircraft action flow in the LTO cycle. With the purpose of estimating the mass of gaseous and particulate matter emissions, the duration of each phase of flight, and the average fuel flow rate in each phase of flight are needed as inputs. According to the study of Swiss FOCA, the piston engine emissions factor of the phase of take-off was suggested to be used for calculating the emissions in the phase of climb-out, because the piston engine mode in the take-off phase is the same as the mode in the climb-out phase under 3000 feet AGL[16]. According to the ICAO reference definitions of phases of flight in LTO for aviation emissions assessment, as well as the characteristics of piston engine performance in each phase of flight, we proposed a model of identifying the phases of flight in GA LTO with the Garmin G1000 data (see Table 4). In the model, we adopt the suggestion from FOCA to combine the phases of take-off and climb-out, and also include the approach descent as part of the phase of approach.

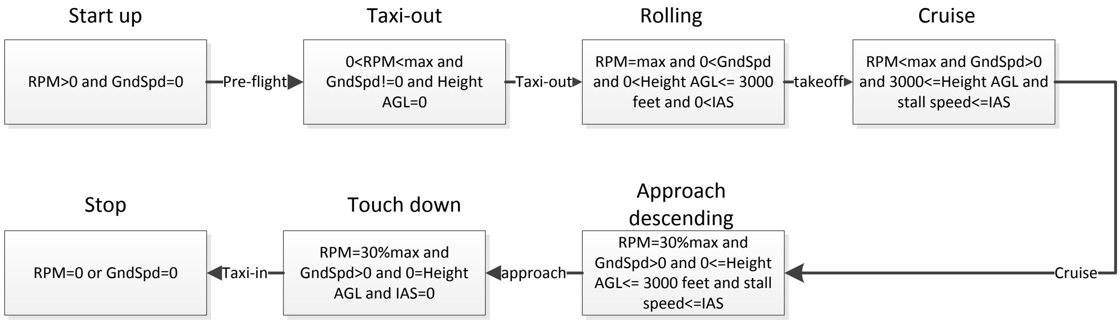


Figure 2. Aircraft action flow in LTO cycle

Table 4. Model tested for identifying the phases of flight in GA LTO with Garmin G1000 Data

LTO Phase	**A/C Actions**	**Avionic Parameters at Transition**
	Start-up	0<RPM and GndSpd=0
Pre-flight	Hold position, pre-flight check	
	Begin to taxi out	0<RPM<max value and Height AGL=0 and 0<GndSpd
Taxi-out	Taxi out or hold position according to ATC	
	Line up and rolling	RPM=max value and 0<GndSpd and Height AGL=0
Take off/Climb-out	Take off and climb out	
	Climb to 3000ft AGL or cruise altitude	RPM<max value and stall speed<IAS and 0<GndSpd and 3000ft (915m)<= Height AGL
Cruise/Out of LTO cycle	Fly at cruise flight level	
	Approach Descend	[0<GndSpd and 0<Height AGL<3000ft (915m) and stall speed<IAS and Pitch deg <0] or RPM=30% max value
Approach	Approach	
	Touch down and exit runway	Height AGL=0 and IAS=0 and 0<GndSpd and RPM<max value
Taxi-in	Taxi in or hold position according to ATC	
	Stop at stand position	GndSpd=0 and RPM=0

C. Model Outputs

In this paper, the Purdue University Airport is treated as the research target, and a GA LTO cycle was developed with our LTO model. We classified flights by inbound and outbound. Each inbound flight contains the phases of approach and taxi-in, and each outbound flight contains the phases of preflight, taxi-out and take-off. Here, we identified all phases of flight defined by our model, excluding the phase of cruise, which is not considered into the LTO cycle for EDMS. Figure 3 shows an example of cross-country flight profile from Monroe County Airport (KBMG), Bloomington, Indiana to Purdue

University Airport (KLAF). Figure 4 shows an example of cross-country training flight profile. This aircraft departed from KLAF, did a touch-and-go training at University of Illinois-Willard Airport (KCMI), Champaign/Urbana, Illinois, and then returned to KLAF. Figure 5 shows an example of local traffic pattern training over Purdue University Airport. This aircraft performed around 80 minutes of local traffic pattern training which includes a go-around. These three figures demonstrate the major flight missions of Purdue Cirrus SR-20 training fleet.

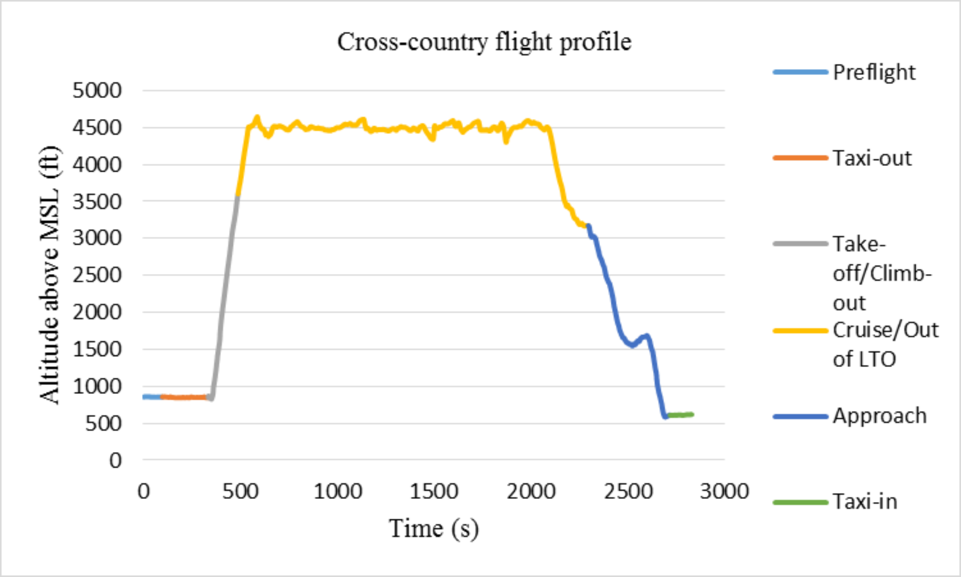


Figure 3. Flight Profile of Cross-country Flight

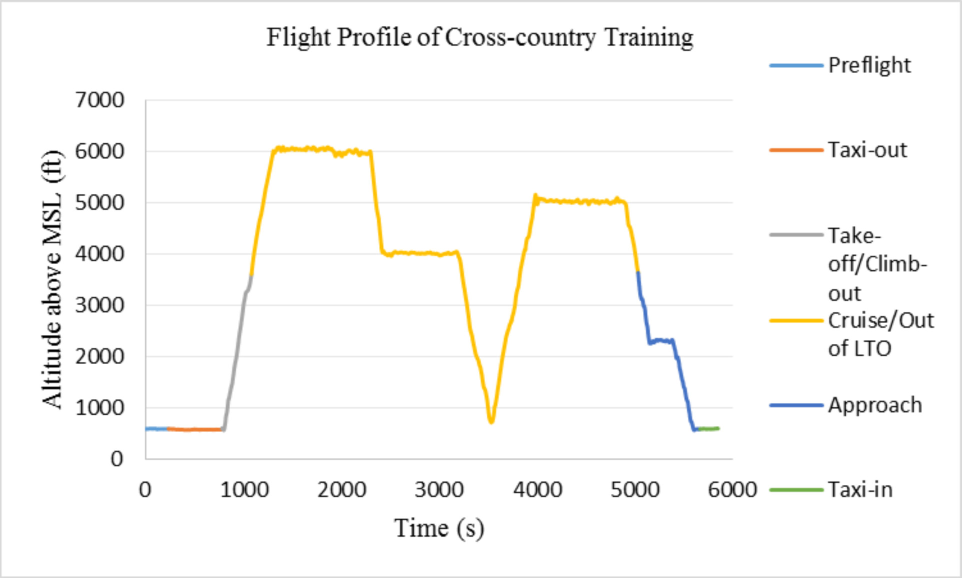


Figure 4. Flight Profile of Cross-country Flight Training

Figure 5. Flight Profile of Local Traffic Pattern Training

In our sample flight data, we extracted 16 sets of outbound flight data, 18 sets of inbound flight data. The phases of Preflight, Taxi-out, and Take-off are identified from outbound flight data. The phases of Approach and Taxi-in are identified from inbound flight data. Outputs of the time in each phase of flight and the average fuel flow rate are computing from sample data. Table 5 shows the computing results of outbound flight data. Table 6 shows the computing results of inbound flight data.

Table 5. Output of Duration and Average Fuel Flow Rate in Each Phase of Outbound Flights. Note: DUR=Duration (minutes), FFR=Average Fuel Flow Rate (gph)

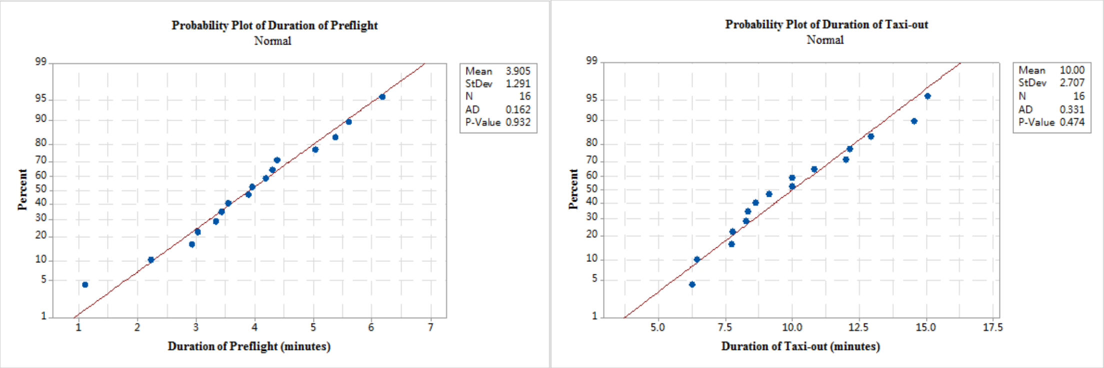
Data Set	**Preflight**		**Taxi-out**		**Take-off/Climb-out**	
Outbound	**DUR**	**FFR**	**DUR**	**FFR**	**DUR**	**FFR**
1	5.37	2.40	8.62	2.89	5.14	14.71
2	3.55	2.03	10.83	2.40	3.20	18.17
3	4.38	1.94	14.57	2.05	4.28	17.05
4	4.18	2.14	8.32	2.56	3.52	17.93
5	2.23	1.94	6.43	2.35	3.93	17.16
6	3.33	2.06	8.27	2.02	3.95	16.17
7	6.18	1.81	12.02	2.15	3.77	16.20
8	3.43	2.00	12.93	2.02	3.63	16.10
9	5.03	2.14	6.25	2.38	4.45	16.86
10	3.89	1.85	7.72	2.15	5.37	16.95
11	3.95	2.09	9.12	2.31	5.02	14.89
12	2.93	1.94	7.77	2.18	4.2	16.60
13	3.03	2.06	10.00	2.08	4.32	16.22
14	5.60	2.27	12.13	2.96	3.92	17.45
15	4.30	2.31	9.98	2.61	3.73	17.08
16	1.10	2.80	15.07	2.67	5.40	16.17

Table 6. Output of Duration and Average Fuel Flow Rate in Each Phase of Outbound Flights.
Note: DUR=Duration (minutes), FFR=Average Fuel Flow Rate (gph)

Data Set	Approach		Taxi-in	
Inbound	**DUR**	**FFR**	**DUR**	**FFR**
1	4.97	4.52	5.22	2.10
2	6.10	4.69	5.30	2.16
3	6.50	6.13	2.37	2.29
4	9.89	5.74	7.57	2.11
5	7.42	6.37	5.68	1.72
6	6.82	6.46	4.29	2.00
7	7.18	6.18	4.73	2.01
8	8.70	6.37	4.7	1.72
9	6.40	6.11	3.82	2.06
10	8.92	5.64	4.68	2.15
11	4.16	6.12	3.62	2.28
12	7.60	5.74	3.03	2.25
13	4.12	5.97	5.27	2.09
14	10.53	6.25	3.08	2.11
15	6.38	6.22	4.32	2.08
16	6.63	5.87	3.60	2.51
17	6.60	5.04	4.75	2.23
18	7.25	6.02	1.87	2.15

III. Output Analysis and Discussion

Descriptive statistical analysis was conducted on the data. Normality of output distributions was determined using the Anderson-Darling (AD) test for normality. If the p-value for the AD test is less than a critical α=0.05, then the distribution can be shown to be not normal. If we fail to reject the null hypothesis (H_0), therefore, we believe that the distribution of the population parameter to be normal. When the p-value is larger than the critical α, the AD statistic gets smaller, and the better the data fits the Normal distribution.



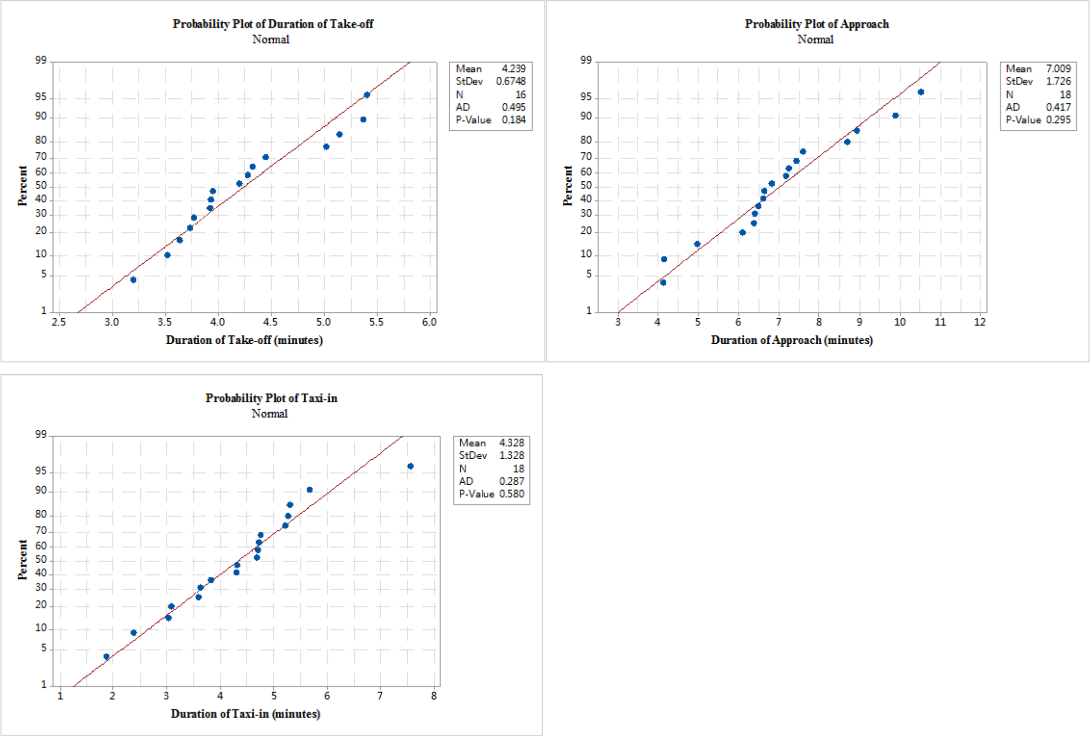


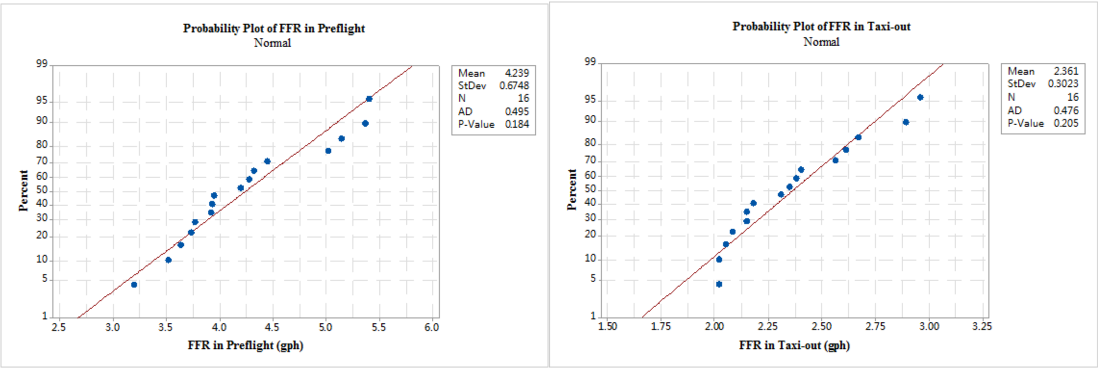
Figure 6. Anderson-Darling Normality Test on the Outputs of Duration in Phases of Flight

Table 7. Statistical Characteristics of Output of Duration (DUR) in Each Phase of Flight

Phase of Flight	n	Mean	Median	StDev	p-value	AD statistic
Preflight	16	3.91	3.92	1.29	0.932	0.162
Taxi-out	16	10.00	9.55	2.71	0.474	0.331
Take-off/Climb-out	16	4.24	4.08	0.68	0.184	0.495
Approach	18	7.01	6.73	1.73	0.295	0.417
Taxi-in	18	4.33	4.50	1.33	0.580	0.287

Note: No parameter believed to not come from a Normal distribution. Critical α=0.05

The Anderson-Darling normality test indicates the duration data of each phase of flight appear to be from a Normal distribution, as there is no statistical evidence to reject the null hypothesis. However, the duration of the phase of taxi-out shows a standard deviation that is large compared to its mean. Two factors may contributed this phenomenon: 1) the limited sample size, and 2) flight data are flight training missions where students spend a certain amount of time on preflight with a standard procedure. However, the irregularity of aircraft ground movement when taxiing out could be caused by operation of pilot training students or the nature of flight slot scheduling.



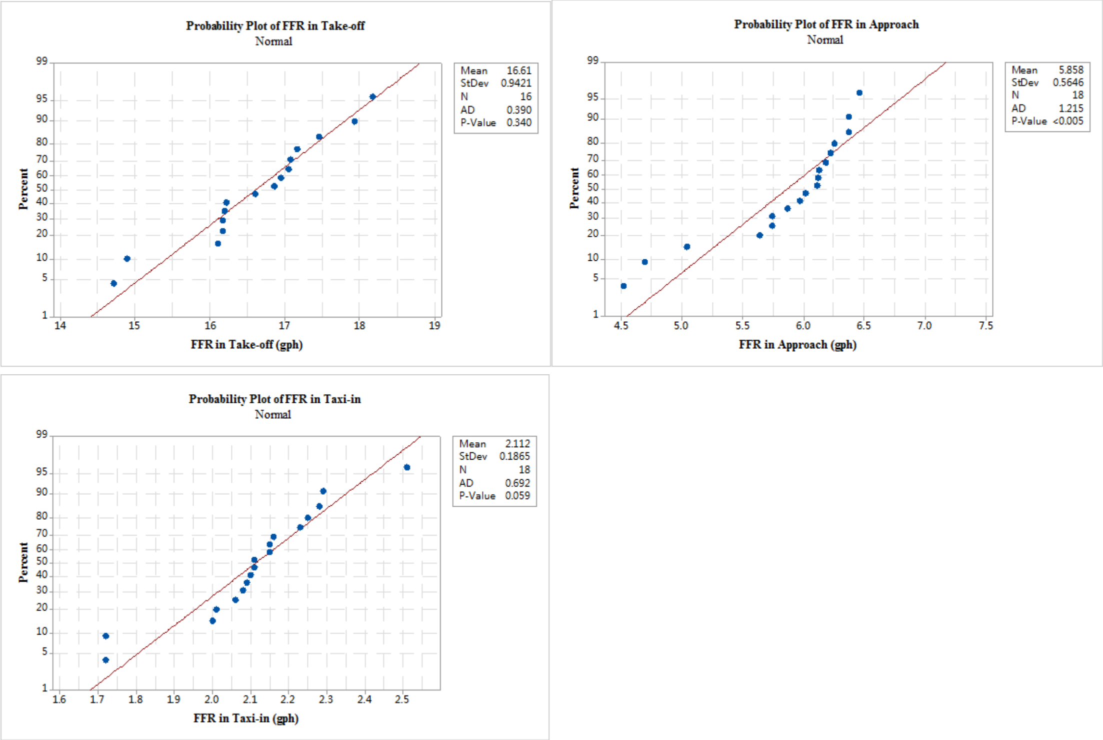


Figure 7. Anderson-Darling Normality Test on the Outputs of Duration in Phases of Flight

Table 8. Statistical Characteristics of Output of Average Fuel Flow Rate (FFR) in Each Phase of Flight

Phase of Flight	N	Mean	Median	StDev	p-value	AD statistic
Preflight	16	4.24	4.08	0.68	0.184	0.495
Taxi-out	16	2.36	2.33	0.30	0.205	0.476
Take-off/Climb-out	16	16.61	16.73	0.94	0.340	0.390
Approach	18	5.86	6.07	0.57	<0.005*	1.215
Taxi-in	18	2.11	2.11	0.19	0.059	0.692

Note: * statistical significant at critical α=0.05; data not believed to come from a Normal distribution.

The Anderson-Darling normality test of average fuel flow rate data indicates the FFR in each phase of flight, except the approach, are normally distributed. We are able to provide statistical significant evidence that the FFR data distribution in the phase of approach is not normal because of the p-value of 0.005 is smaller than critical α=0.05. The summary of the descriptive statistics of our FFR output in the phase of approach shows two concentrations of data (see figure 8). Two reasons might explain this phenomenon: 1) the limited sample size, and 2) we refer to the ICAO’s definition of the LTO to determine the phase of approach in our model where the approach starts from the beginning of approach descent to the touch-down, pilot students might change the engine mode in the phase of approach to adjust aircraft attitude and speed for landing, and approach FFR is much more affected by airport weather conditions; however, approach would perhaps be more smooth for experienced pilots. In that case, the FFR in approach might fit a distribution other than Normal.

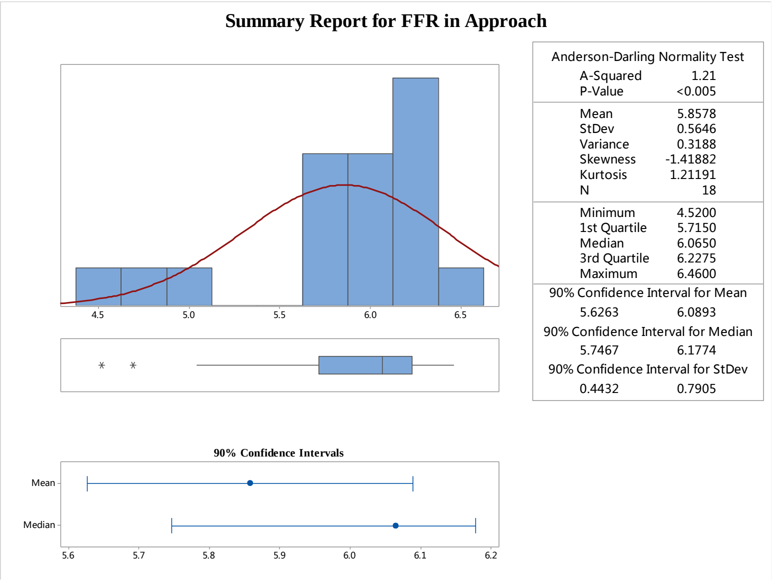
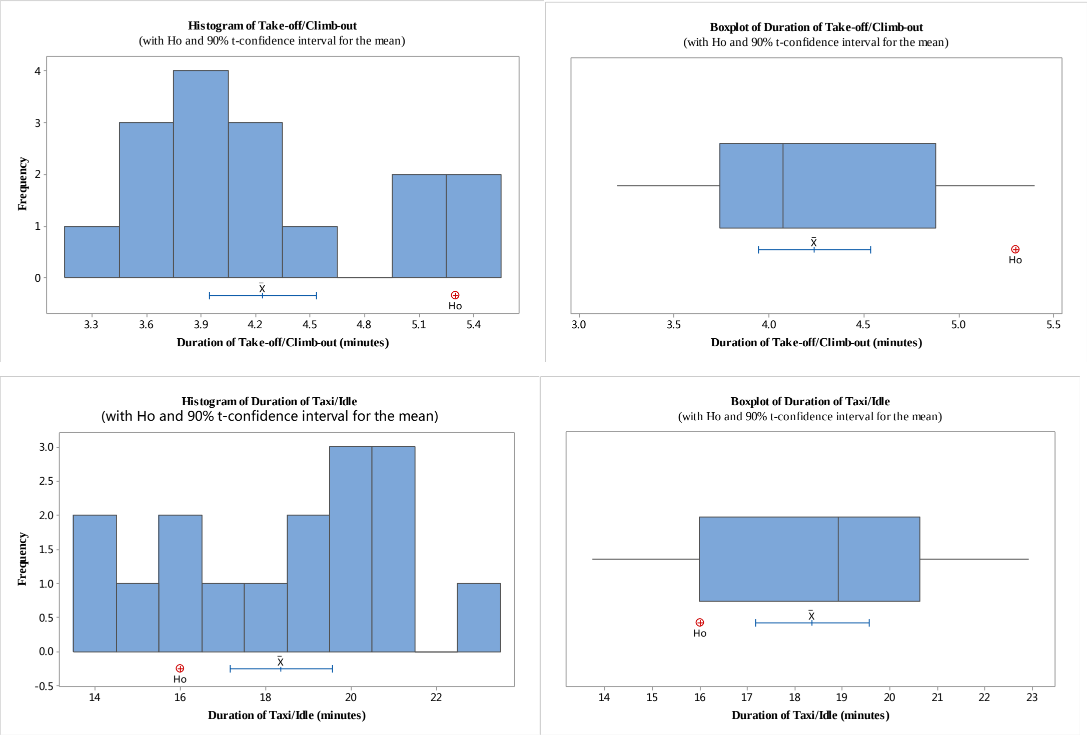


Figure 8. The Statistics of the FFR in Approach

The outputs of durations in each phase are apparently different from ICAO's reference for the duration of phases of flight in LTO cycle, because ICAO's LTO reference is primarily for commercial flight of turbine engine aircraft. For US EPA and Swiss FOCA's reference on the LTO cycle, we used a t-test to compare our outputs of durations to their recommended values.

We assume the null hypothesis that the mean value of our output of duration has no significant difference with ICAO and US EPA/FOCA's reference, if the p-value for the t-test is less than a critical α=0.05, then the mean value of durations from our model has significant difference with the value from corresponding organization, which means we fail to reject the null hypothesis (H_0).



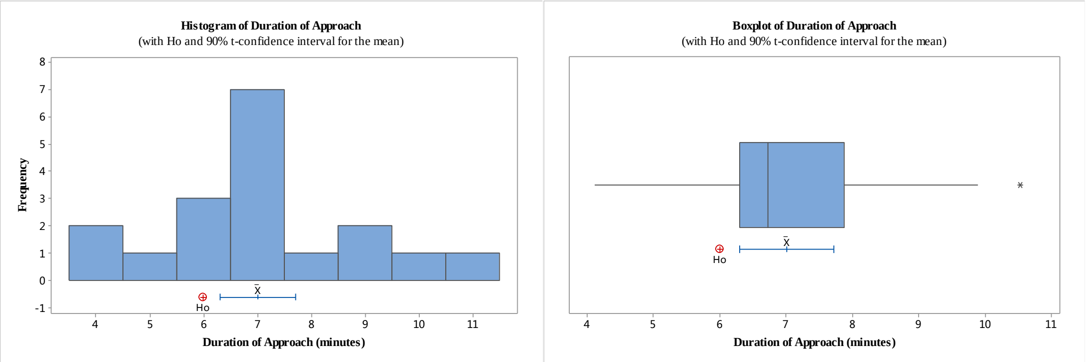


Figure 9. The graphical description of one-sample t-test results of the duration of each phase of flight

Table 9. The result of one-sample t-test of the duration of each phase of flight

Mode	FOCA Reference Duration in Mode for Piston Engine (Minutes)	US EPA Reference Duration in Mode for Piston Engine (Minutes)	Output of Model (Minutes)	p-value (for t-test $\mu_1=\mu_2$)
Take-off	0.3	0.3	4.2	0.000*
Climb-out	5.0	5.0		
Cruise	-	-	-	-
Approach	6.0	6.0	7.0	0.024*
Taxi/Idle	16.0	16.0	18.3	0.003*

Note: * significant at α=0.05

The one-sample t-test results show the durations of each phase of flight generated by our model are statistical significantly different from the recommended values by US EPA or Swiss FOCA with a confidence interval of 95%. Further work is needed to see if a larger number of flights over a longer time period will have the same results.

In order to exclude the possibility that the difference between the outputs of our model and the US EPA/Swiss FOCA's recommended duration in each phase of flight is caused by the limited sample size, we determined the required sample size for estimating the true average duration of phases of flight with a 90% confidence level and a margin of error of ±10%. If the required sample size is larger than what we currently have, then we recommend that larger samples be used in future studies. The required sample sizes are shown in Table 10. The required sample size shows only the current sample size for the Take-off/Climb-out satisfies the required sample size Therefore, based on this exploratory study, we recommend that a sample of at least 32 flights be used in future studies.

Table 10. The Required Sample Size for Estimating the Duration of Phases of Flight

Phase of Flight	Current Sample Size	Mean	StDev	Margin of Error (±10%)	Required Sample Size
Preflight	16	3.91	1.29	± 0.391	32
Taxi-out	16	10.00	2.71	± 1.000	22
Take-off/Climb-out	16	4.24	0.68	± 0.424	9
Approach	18	7.01	1.73	± 0.701	19
Taxi-in	18	4.33	1.33	± 0.433	28

Note: critical α=0.05

IV. Conclusion

This study explored an accurate method of determining a GA landing and takeoff (LTO) cycle for exhaust emissions analyses. Considering the flight performance of piston-engine aircraft and the operational characteristics of General Aviation, we proposed a model of estimating the average duration and the average fuel flow rate of General Aviation landing and take-off (LTO) cycle by identifying phases of flight based on the ICAO Annex 16, Volume II LTO guidelines, US EPA guidelines, and Swiss FOCA guidelines. We imported de-identified flight sample data from the Cirrus SR-20 fleet of Purdue University to test this model. By statistically analyzing the outputs of duration and fuel flow rate, and comparing the outputs to the existing recommended values by US EPA and Swiss FOCA, we noticed our outputs were statistically different (alpha = 0.05) from the recommended values. Possible reasons for the difference are: 1) the limited sample size we acquired, 2) flight data come from the aircraft which are primarily used for training, 3) diverse flight missions include local traffic pattern training, cross-country training, and 4) other factors making it hard to identify the phases of flight.

In order to exclude determine the causes of the deviation of outputs, and verify the accuracy of this model the next step is to include larger sample sizes and flight data from other airports or from organizations with less diverse flight missions. An automated model of calculating the average duration and the average fuel flow rate would enhance the accuracy of estimating the mass of gaseous and particulate matter emissions from General Aviation over LTO cycle with the corresponding emission index of aircraft engine.

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