Emissions of piston engine aircraft using aviation gasoline (avgas) and motor gasoline (mogas) as fuel – a review

K Thanikasalam\textsuperscript{1}, M Rahmat\textsuperscript{1}, A G Mohammad Fahmi\textsuperscript{2}, A M Zulkifli\textsuperscript{1}, N Noor Shawal\textsuperscript{1}, K Ilanchelvi\textsuperscript{3}, M Ananth\textsuperscript{3}, R Elayarasan\textsuperscript{1}

\textsuperscript{1}Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor, Malaysia
\textsuperscript{2}Department of Aeronautical Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Batu Pahat, Johor, Malaysia
\textsuperscript{3}Department of Chemical Engineering, Universiti Malaysia Sabah (UMS), 88400 Kota Kinabalu, Sabah, Malaysia

E-mail: insp466@hotmail.com

Abstract. There are two categories of aircraft engines, namely, piston and gas turbine engines. Piston engine extracts energy from a combustion compartment through a piston and crank apparatus that engages the propellers, which in turn, provides an aircraft the needed momentum. On the other hand, gas turbine engine heats a compressed air in the combustion compartment resulting in propulsion that drives an aircraft. Piston engine aircrafts might appear small but together thousands of piston engine aircraft, which encompasses a bulk of the general aviation fleet, present a considerable health threat. That is because these aircraft, which depend on avgas and mogas to run, comprise major remaining sources of lead emissions. People exposed to even small levels of lead, particularly children, have tendencies to suffer from cognitive and neurological harm. Dissimilar from commercial airliners that do not utilize leaded fuels, piston engine aircraft account for nearly half of the lead discharge in skies. But, what is the extent of the impact caused by these airborne emissions on the country’s economy and public health? To answer this query, a thorough literature review on emissions of piston engine aircraft ought to be undertaken. This article conducts a literature review on emissions of piston engine aircraft using avgas as fuel and mogas as fuel.

1. Introduction
Piston engines are the improvements of steam engines that first emerged during the 17th century. Czarnigowski et al. 2010 provide a brief background on piston engines. Czarnigowski et al. 2010 say that steam engines utilize the heat generated to create steam pressure that is then used to produce a rotating motion. Steam engines were in time applied to drive nearly all mechanical apparatus including the first railway trains and aircraft. In contemporary aircraft piston engine, gas propulsion substitutes steam in producing pressure to drive the engine. According to Czarnigowski et al. 2010, one or more cylinders characterise the piston engine. The cylinders contain a comfortably fitting piston that is capable of moving freely forward and rear inside the cylinder. Every piston attaches to a crankshaft through a connecting rod.

Czarnigowski et al. 2010 write that when fuel enters and ignites inside the cylinder, the scorching gases generated inflate with incredible force and drives the piston frontward in the cylinder that in
turns move the piston rod forward causing the crankshaft to revolve. The full revolution of the crankshaft thrust the piston in the rear direction into the cylinder before the cycle commences again. Czarnigowski et al. 2010 claim that it is the crankshaft, which transfers the reciprocating and linear movement of the piston into the rotary motion that pushes the propeller. Czarnigowski et al. 2010 claim that piston engines were employed in powering all aircraft up until jet engines were made during the early 20th century, motivated by the need for an aircraft that could fly at superior speeds and elevated altitudes. Currently, piston engine aircraft are still popular for both private and commercial use owing to their reduced cost of entry and reliable performance.

Federal Aviation Administration (2005) provides a brief summary of significant issues concerning aviation emissions. Aircraft generate similar types of emissions like an automobile. According to Federal Aviation Administration (2005), piston aircraft jet engines, like automobiles engines, emit carbon dioxide, water vapour, nitrogen oxides, and carbon monoxide, and hydrocarbon emissions. However, unlike automobile engines, piston aircraft jet engines generate lead emissions.

Federal Aviation Administration (2005) data suggests that aircraft engine emissions comprise around 70% carbon dioxide, roughly 29% water vapour, and less than 1% of carbon monoxide and nitrogen oxide emissions. Aircraft emissions, based on whether they happen near the earth surface or at higher altitudes, are mainly deemed local air quality contaminants or greenhouse gas emissions, respectively. Water released by aircraft engines at altitude can trigger greenhouse effect. Around 10% of aircraft emissions of every form, apart from hydrocarbons and carbon dioxide, are generated during ground level manoeuvres and during takeoff and landing processes. According to Federal Aviation Administration (2005), a considerable amount of aircraft emissions, nearly 90% happen at higher altitudes. Concerning hydrocarbons and carbon monoxide, the split is around 30% emissions at ground level and 70% emissions at higher altitudes. Federal Aviation Administration (2005) argues that aviation emissions reveal the intensity of general aviation activity. The expansion of air travel in the last numerous decades has been very speedy. The need for travel services both cargo and passenger hauling is increasing considerably. Federal Aviation Administration (2005) argues that this also implies that aviation emissions have increased over time.

2. **Aircraft Piston Engine Exhaust Emissions Symposium**

Lewis Research Center (1976) focuses on piston engine emissions. The study notes that the published literature has little information on piston engine aircraft emissions. Thus, they suggest that more researches are required to fill the knowledge gap in piston engine aircraft emissions. This symposium report notes that piston aircraft jet engines, like automobiles engines, emit carbon dioxide, water vapour, nitrogen oxides, and carbon monoxide, and hydrocarbon emissions. Nevertheless, contrasting automobile engines, piston aircraft jet engines generate lead emissions. The findings by Lewis Research Center (1976) indicate that piston engine aircraft emissions standards fail to meet the standards set by Environmental Protection Agency (EPA) lead, hydrocarbon, and carbon monoxide.

This symposium report also claims that people exposed to even small levels of lead, particularly children, have tendencies to suffer from cognitive and neurological harm [9]. Dissimilar from commercial airliners that do not utilize leaded fuels, piston engine aircraft account for nearly half of the lead discharge in skies. To understand the extent of the impact caused by these airborne emissions on a global economy and public health, Lewis Research Center (1976) suggests that more research should be undertaken on piston engine emissions.

3. **Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution**

Masiol and Harrison (2014) also claim that engines for both general and civil aviation are normally categorized as piston or gas turbine engines. Aviation piston engines operate on AVGAS as fuel. Masiol and Harrison (2014) asserts that piston engines are usually installed in small-sized aircraft normally associated to private use, flying associations, flight instruction, farming, and tourism. Piston engines operate using the same fundamental principles used by spark ignition engines for automobiles.
but normally need higher performance. According to Masiol and Harrison (2014), the major variation between gas turbine engines and piston engines is that combustion is incessant in gas turbine engines and alternating in piston engines.

The accessibility of dependable data on fuel consumption is necessary to make authoritative approximations of aviation emissions at international and national scales. Masiol and Harrison (2014) claim that a number of approximations of aviation fuel utilization presented in existing literature generally refer only to gas turbine engines since piston-powered engines are assumed to account for nearly 2% of propeller fuel burn. Masiol and Harrison (2014) approximated that up to $169 \times 10^3$ g fuel was used internationally in the years 2000. Of this, nearly $152 \times 10^3$ g was used in civil flights. In addition, Masiol and Harrison (2014) indicated that AERO2k international aviation emissions inventories recorded that $176 \times 10^3$ g of kerosene were utilized in the year 2002. After methodically reviewing existing literature, Masiol and Harrison (2014) concluded that the existing information on the effect of emissions of piston engine aircraft is insufficient and the impacts of future expansion in the quantity of air traffic are very problematic to predict. Masiol and Harrison (2014) concluded that quantification of the effect of emissions of piston engine aircraft on domestic air quality is very challenging owing to the intricacy of air emissions and the existence of considerable levels of contamination from other sources.

4. Modelling and measurement of aircraft engine emissions inside the airport area
Zaporozhets and Synylo (2015) explore the role aviation emissions contribute towards greenhouse gas issues. This study notes that a number of emissions from piston engine aircraft occur at higher altitudes. These emissions generate greenhouse gases that likely contribute to climate change. Zaporozhets and Synylo (2015) also suggest that under specific conditions, piston engine exhaust may generate contrails. Internationally, scientists are exploring the possible effects of these contrails to understand if they have a considerable effect on the greenhouse effect. Zaporozhets and Synylo (2015) argue that concerns about greenhouse gas emissions have increased worldwide. While there are numerous greenhouse gases, this study suggests that carbon dioxide and nitrogen oxide emissions are usually most pertinent from an aviation viewpoint.

Zaporozhets and Synylo (2015) also illustrate greenhouse gas emissions based on countries. The analysis indicates that land transportation emissions contribute 27% of greenhouse gas inventory, while aviation emissions contribute around 2.7%. In addition, the analysis illustrates that global greenhouse gas emissions have increased in the last decade and are anticipated to increase further in the coming years. Zaporozhets and Synylo (2015) point out that there many ongoing initiatives aimed at reducing emissions both at the airport and in the national aviation system. First, there are numerous voluntary ventures in progress at airports to lessen emissions from ground support apparatus and other airport automobiles. For instance, FAA is developing a pilot program in collaboration with DOE and EPA, aimed at demonstrating air quality enhancement with substitute fuel ground support apparatus. Zaporozhets and Synylo (2015) also reveal that many airports are independently taking action to lessen emissions from buses, tractors, trucks, taxis, and other on-road automobiles, which operate around the airports. Concerning piston engine modifications, Zaporozhets and Synylo (2015) suggest that there exist multifaceted emission interrelationships. This makes it hard to alter its design as a mitigation approach because it introduces a tradeoff among particular contaminants, emissions, and noise.

5. Aircraft piston engine emissions summary report - Switzerland
Federal Office of Civil Aviation (2007) suggests that aircraft piston engines use aviation AVGAS as fuel. It claims that aircraft piston engines are commonly referred as "small propeller aircraft". On an international scale, piston engine aircraft use a comparatively small share of fuel. Federal Office of Civil Aviation (2007) notes that in Switzerland the yearly fuel use by aircraft piston engines is fewer compared to fuel used in gardening activities. Federal Office of Civil Aviation (2007) also points out that emissions generated by aircraft have often attracted little attention. Globally, experts have
expressed little efforts to come up with emission standardization for such engines. Federal Office of Civil Aviation (2007) also notes that information regarding emissions from aircraft piston engines is practically missing. This shortage has occasionally caused challenges, especially when producing a comprehensive aircraft emissions catalogue or when providing reliable data on an ecological impact assessment. Federal Office of Civil Aviation (2007) undertook an exploratory experiment to fill this gap of knowledge.

Federal Office of Civil Aviation (2007) findings indicate the contribution of piston engine aircraft discharges on Switzerland’s civil aviation emission. The findings disclose that piston engine aircraft contribute less than 1% of the total civil aviation carbon dioxide emissions. Federal Office of Civil Aviation (2007) also reveals that these engines contribute 1% share on nitrogen oxides, 10% share of hydrocarbons, 40% share of Carbon monoxide, and 100% share of the lead. In the findings, Federal Office of Civil Aviation (2007) claims that carbon monoxide and hydrocarbon emissions are significant during landing and take-off phase. In spite of a fuel burn, which is more than a few magnitudes lesser, carbon monoxide and hydrocarbon emissions might reach the amount produced by large aircraft. Federal Office of Civil Aviation (2007) argues that this phenomenon has been caused by aircraft piston engine’s technology that has been at a standstill ever since the 1960s.

6. Exhaust Emissions Characteristics for a General Aviation Light-Aircraft Avco Lycoming IO-360-B1BD Piston Engine

Becker (1979) conducted emission tests on a general aviation piston engine to determine emission characteristics, establish the impact of leaning-out of gasoline metering system on exhaust discharges, authenticate the suitability of test processes, testing procedures, and instrumentation. The tests also sought to identify a drop in operating confines and safety boundaries ensuing from fuel adjustments appraised for enhanced piston engine exhaust emissions attributes [1]. The tests were done at “National Aviation Facility Experimental Centre,” USA.

The findings by Becker (1979) reveal that engine IO-360-B1BD failed to meet the 1979/1980 standards set by Environmental Protection Agency (EPA) on hydrocarbon and carbon monoxide. The engine only met the EPA standards on nitrogen oxides. Becker (1979) also suggests that the engine gasoline metering system could be attuned on the test plunk to lessen the current carbon monoxide exhaust emission levels, although not to levels needed by EPA standards, under the most strict LTO cycle necessities. It was also noted that the engine could be attuned on the test plunk to lessen the unutilized hydrocarbon exhaust emission levels, however not to levels needed by EPA [1]. After testing engine IO-360-B1BD, Becker (1979) concluded that simple fuel management modification like varying of fuel schedule, do not offer the sole capacity to safely lessen piston engine exhaust emissions. The test data also revealed that fuel management alterations ought to be integrated with engine cooling variations prior safe and optimal low-emission aircraft-engine blend is attained. Becker (1979) also noted that spark settings, excluding the 25° BTC setting, fail to generate considerable beneficial enhancements in exhaust emissions. In addition, the EPA carbon monoxide limit of 0.0420 lb/cycle/rated BHP seemed unachievable when hot-day take-off and ascending necessities are affected by aircraft’s heavy gross weight plus the requirement to pay vigilant consideration to CHT confines.

7. Exhaust emissions from in-use general aviation aircraft

Yacovitch (2016) also claims that piston engine aircraft emissions data either are missing or have not been autonomously confirmed. Yacovitch et al. (2016) sought to fill this gap of knowledge by providing the results from an emissions test. For this test, the researchers assessed emissions and calculated emission indices for numerous in-use aircraft. Yacovitch et al. (2016) document 47 complete engine tests comprising 10 engines from a category of a top 20 general piston engines. The researchers noted that numerous factors may influence emissions. Yacovitch et al. (2016) explored a number of sources for high inconsistencies in emission indices. The research team noted that pilot’s way of thinking coupled with his or her operation experience of an aircraft influences combustion factors. Yacovitch et al. (2016) also explored a number of technical information linked with piston
engines. Aircraft emissions like trends in particle mass and unpredictability, the impact of fuel additives, and thermal generation of nitrogen oxides and its relations to lean combustion.

The findings by Yacovitch et al. (2016) suggest that piston and gas turbine engines have very dissimilar emissions, with respect to their magnitude and power trends. The disparities may be understood in regards to the higher combustion performance in contemporary gas turbine engines opposed to piston engines. Thus, piston engines release more hydrocarbons and carbon monoxide emissions and a smaller amount nitrogen oxide compared with gas turbine engines. Yacovitch et al. (2016) also reveal warped distributions of emission indices recorded from an experiment assessing emissions of hydrocarbons, nitrogen oxides, and impure matter from a piston engine. The findings indicated that the most general emission index is not equivalent to the approximate emission index. Notably, Yacovitch et al. (2016) claim that carbon monoxide emissions’ distributions were not skewed.

8. **Advance Notice of Proposed Rulemaking on Lead Emissions from Piston-Engine Aircraft Using Leaded Aviation Gasoline - Regulatory Announcement**

Environmental Protection Agency (2010) represents an advance notice to illustrate information at present available and those being collected, which will be applied by the proprietor to issue an ensuing proposal concerning whether, in the proprietor’s decision, piston aircraft lead emissions cause or add to air pollution that might reasonably be expected to jeopardize public health or well-being. In this notice, Environmental Protection Agency (2010) describes and requests observations on the existing data for appraising lead emissions, atmospheric concentrations, and possible exposure to lead through continuous use of leaded aviation gasoline in piston engine aircraft. The agency also describes and requests commentaries on further data being collected, which will update any future decision.

The findings by Environmental Protection Agency (2010) indicate that lead emissions from piston engine aircraft consist of roughly half of the countrywide catalogue of lead released into the air. Environmental Protection Agency (2010) suggests that there are around 20,000 airport services in the US that use leaded aviation gases. The agency asserts that positive contribute findings on lead emissions prompt EPA’s responsibility to create emission standards. In deliberating emission standards, the agency asserts that EPA should deliberate controlling piston engines reliant on AVGAS. Environmental Protection Agency (2010) proposes that EPA in collaboration with FAA should consider evaluating the technical viability of a probable phase-down or abolition of leaded AVGAS. One alternative to consider, for instance, is an emissions standard, which will order all newly-designed aviation piston engines to run successfully on unleaded AVGAS. However, Environmental Protection Agency (2010) recognizes that a huge challenge exists in addressing lead emissions from the in-use fleet. Renovating in-use aircraft piston engines to run on unleaded AVGAs will require a considerable logistical and technical challenge.

9. **Non-road Large Spark-Ignition Engines: Exhaust and Evaporative Emission Standards**

Office of Transportation and Air Quality (2016) focuses on evaporative and exhaust emission standards. The agency argues that numerical emission sets for hydrocarbons ought to be met with respect to the following forms of hydrocarbon discharges for engines operating on (1) non-methane hydrocarbon fuels, (2) total hydrocarbon equivalent and (3) total hydrocarbons for natural gas, alcohol, and other fuels respectively. Similarly, the agency provides “Voluntary Blue Sky” standards required for spark-ignition (SI) aviation engines. Office of Transportation and Air Quality (2016) suggests that engines that have displacement below 1,000 CC with maximum power below 30 kW should be categorized and certified as small SI engines. According to Office of Transportation and Air Quality (2016), emission standards rely on evaluation over a steady-state duty-cycle. The agency asserts that the Tier-I hydrocarbon plus nitrogen oxide emission standard used during the evaluation is 5.40 grams per kW-hour.

In addition, Office of Transportation and Air Quality (2016) express piston engine useful life in terms of years and hours, which are the least useful life necessities. Concerning severe-duty engines,
the least useful life is 1500 hours or seven years of service. Office of Transportation and Air Quality (2016) suggests that an extended useful life in hours is needed if: (1) the engine is intended to run longer than the least useful life reliant on the suggested rebuild interval; or (2) the fundamental engine warranty is longer compared with the least useful life. An extended warranty period of 3, 500 hours or five years of service is applicable for expensive warranted parts. Office of Transportation and Air Quality (2016) also claims that optional engine certification is permitted based on the following formula: “(HC+NOx) × CO0.784 ≤ 8.57.”

10. Emissions of air pollutants from civil aviation in the Netherlands
Hulskotte (2017) investigates air population emissions in one airport in Netherlands. The investigation uses CLEO model, a methodology derived from an internationally established approach used by EPA. The model approximates emissions from takeoff and landing cycles using aboard auxiliary power units. Emissions occurring at high altitudes were not considered part of the tests. The findings by Hulskotte (2017) illustrate that nitrogen oxide emissions attributed to civil aviation have increased by nearly 140% between the years 1990 to 2015. Hulskotte (2017) also notes that between 1990 and 1995, hydrocarbon emissions have lessened by 14%. 380 tons of hydrocarbon emission occurred in the year 2015. Around 25% of these emissions are attributed to fuel handling. Carbon monoxide emissions also reduced by 4% over the same period. In the year 2015, 3.5 tonnes of carbon monoxide were recorded. These findings indicate that current aircraft engines release less hydrocarbon and carbon dioxides but have barely improved with respect to nitrogen oxide emissions.

In addition, the findings by Hulskotte (2017) indicate that piston engine aircraft operating on AVGAS contribute a small portion of nitrogen oxide emissions, a share of less than 1%. However, the investigations show that piston engine aircraft contribute more considerably to carbon monoxide and hydrocarbon emissions, a share of more than 5%. Furthermore, the use of AVGAS by piston engine aircraft proved to be a key source of aviation lead emissions. The investigations by Hulskotte (2017) revealed that up to 0.8 tonnes of lead emissions were recorded in the years 2015. Piston engine aircraft emissions elements were established using measurement information from US EPA in collaboration with Swiss Federal Office for Civil Aviation [6].

11. New Methodology for Modeling Annual Aircraft Emissions at Airports
Woodmansey and Patterson (1994) presented a methodology for assessing yearly aircraft emissions in airports. This methodology can be used in testing annual piston engine aircraft emissions. Woodmansey and Patterson (1994) assert that accurate approximations of total- aircraft emissions are vital components of any environmental impact appraisal done for any proposed airport expansion. To establish the volume of emissions created by piston engine aircraft, in particular, airport, using the model presented by Woodmansey and Patterson (1994), it is essential to know the emission characteristics of piston engines. However, they point out that the published literature has little information on piston engine aircraft emissions. Thus, they suggest that new methodologies are required to assist in approximating annual emissions from piston engine aircraft at airports. Woodmansey and Patterson (1994) proposed a linear regression equation linking a number of emissions with aircraft weight. Using this approach, they claim that total annual emissions for piston engine powered aircraft like carbon monoxide, nitrogen oxides, carbon dioxide, and lead emissions can be tabulated. The regression model presented by Woodmansey and Patterson (1994) is comparatively simple, quick, and low-priced way of calculating a yearly emission catalogue for an airport.

12. Reduction emission level of harmful components exhaust gases by means of control of parameters influencing on spraying process of biofuel components for aircraft engines
Jankowski (2011) undertook an exploratory study to test fuel additives, that lessen the magnitude of atomised fuel drops, by altering particular that affect the atomisation procedure. These parameters encompass surface tension, thickness, viscosity index, and density. Jankowski (2011) noted that the
magnitude of bio-fuel drops was much larger likened with those of hydrocarbon fuels. By altering the chemical and physical structures of bio-fuels, magnitudes of drops of atomised fuel streams become lesser. Jankowski (2011) claim that these magnitudes play a key role in the level of carbon monoxide and hydrocarbon emissions, in addition to nitrogen oxides emissions. Jankowski (2011) argues that the exploration studies on emissions of lethal elements of fuel are comparatively superior in the field of piston engines, particularly automobile applications.

However, Jankowski (2011) argues that the dynamic expansion of both civic and general aviation presents more pressure on the problem of poisonous emissions by aircraft engines. According to Jankowski (2011), the extent of toxic emissions aircraft engines could be a thousand times more compared to the level of piston engine aircraft emissions. Thus, the problem of how bio-fuel additives may influence the procedure of fuel atomisation and facilitate control over the atomisation in obtaining the least likely drops and subsequently less nitrogen oxide emissions is still a new issue. Jankowski (2011) notes that the reduced nitrogen oxide emission, with respect to the use of bio-fuels, is of greatest implication since new data indicates that its emission levels are on the rise.

13. Piston engine emissions: results of tests and development of test methods

Klueg, Salmon, Becker, and Imbrogno (1978) explain the procedures created by the Federal Aviation Administration in the latest years for testing, gauging, and computing exhaust emissions from piston engines aircraft. This study outlines instrumentation recommended for monitoring emissions piston engine aircraft. The instrumentation comprises apparatus for assessing amounts of carbon monoxide, carbon dioxide, nitric oxides, and hydrocarbons.

Klueg et al (1978) suggest that to identify mass emissions during aircraft landing and takeoff a calculation procedure that utilizes the calculated exhaust concentrations and calculated fuel flow and airflows is adopted. Klueg et al (1978) warn that caution ought to be taken when choosing a computation approach from the published procedures in existing literature to guarantee that the method is valid over the whole operating range of piston engine aircraft and that any suppositions made are precise. The findings by Klueg et al (1978) noted that any effort to enforce engine exhaust emission restrictions without giving due deliberation to engine’s CC, head temperature confines and nacelle cooling may lead to severe troubles. This implies that piston engine modifications present multifaceted emission interrelationships, which make it hard to alter its design as a mitigation approach because it introduces a tradeoff among particular contaminants, emissions, and noise.

14. Conclusion

Based on the above literature review, it should be noted that there is an increasing concern regarding the emissions of piston engine aircraft. Piston engine aircraft might appear small but together thousands of these machines present a considerable health threat. People exposed to even small levels of lead, particularly children, have tendencies to suffer from cognitive and neurological harm. Dissimilar from commercial airliners that do not utilize leaded fuels, piston engine aircraft account for nearly half of the lead discharge in the skies. The literature review also indicates that there is a knowledge gap on emissions of piston engine aircrafts. Thus more researchers should be undertaken on this topic.

Acknowledgement
The authors express their gratitude to the Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia for their financial support.

References
[1] Becker, E., 1979. Exhaust Emissions Characteristics for a General Aviation Light-Aircraft Avco Lycoming IO-360-B1BD Piston Engine.[online] Available from: http://www.dtic.mil/get-tr-doc/pdf?AD=ADA066589 [Accessed 20 Jul. 2017].
[2] Czarnigowski, J., Jakliński, P. and Wendeker, M., 2010. Fuelling of aircraft radial piston
engines by ES95 and 100LL gasoline. *Fuel*, 89 (11), 3568-3578.

[3] Environmental Protection Agency, 2010. *Advance Notice of Proposed Rulemaking on Lead Emissions from Piston-Engine Aircraft Using Leaded Aviation Gasoline - Regulatory Announcement*. [online]. Available from: http://realneo.us/content/advance-notice-proposed-rulemaking-lead-emissions-piston-engine-aircraft-using-leaded-aviation-gasoline [Accessed 20 Jul. 2017].

[4] Federal Aviation Administration, 2005. *Aviation & Emissions A Primer*. [online] Available from:https://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/AEPRIMER.pdf [Accessed 20 Jul. 2017].

[5] Federal Office of Civil Aviation, 2007. *Aircraft piston engine emissions summary report*. [online] Available from: http://www.hjelmco.com/upl/files/2425.pdf [Accessed 20 Jul. 2017].

[6] Hulskotte, I., 2017. *Emissions of air pollutants from civil aviation in the Netherlands*. Princeton: Princeton University.

[7] Jankowski, A., 2011. Reduction emission level of harmful components exhaust gases by means of control of parameters influencing on spraying process of biofuel components for aircraft engines. *Journal of KONES*, 18 (3), 129-134.

[8] Klueg, E., Salmon, R., Becker, E. and Imbrogno, S., 1978. *Piston engine emissions: results of tests and development of test methods*. New Jersey: Federal Aviation Administration.

[9] Lewis Research Center, 1976. *Aircraft piston engine exhaust emissions symposium*. [online] Available from: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770010138.pdf [Accessed 20 Jul. 2017].

[10] Masiol, M. and Harrison, R., 2014. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review. *Atmospheric Environment*, 95 (7), 409-455.

[11] Ng, J. and Gan, S., 2012. Development of emissions predictor equations for a light-duty diesel engine using biodiesel fuel properties. *Fuel*, 95, 544-552.

[12] Office of Transportation and Air Quality, 2016. *Nonroad Large Spark-Ignition Engines: Exhaust and Evaporative Emission Standards*. [online] Available from: cta.ornl.gov/data/tedb35/Spreadsheets/Table12_24.xls [Accessed 20 Jul. 2017].

[13] Rae, J. and Heron, S., 1962. History of the Aircraft Piston Engine. A Brief outline. *Technology and Culture*, 3 (2), 209.

[14] Woodmansey, B. and Patterson, J., 1994. New Methodology for Modeling Annual Aircraft Emissions at Airports. *Journal of Transportation Engineering*, 120 (3), 339-357.

[15] Yacovitch, T., 2016. *Exhaust emissions from in-use general aviation aircraft*. Washington, D.C.: The National Academies Press.

[16] Zaporozhets, O. and Synylo, K., 2015. Modelling and measurement of aircraft engine emissions inside the airport area. *Proceedings of National Aviation University*, 63 (2).