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A MODEL TO ESTIMATE CO_2 EMISSIONS FROM AIR TRAFFIC MOVEMENT IN AIRPORTS

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.

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February 2020

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Abstract

A model to estimate CO_2 emissions from Air Traffic Movement in airports

The importance of airport emission inventory is more specific in the local context as it directly affects the local air quality. The assessment of emission from different phases of flight separately has not received sufficient attention. The specific gap addressed by this research is evaluating the CO_2 emission from different phases of aircraft within the Landing Take-off (LTO) cycle and the CO_2 emission from flight delays since they allow initiating more precise emission reduction strategies. Using currently available methodologies for assessing the emission from the LTO cycle in the Sri Lankan context has significant limitations. Industry-wide standards have been found to overestimate actual volumes specific to local conditions.

Reviewing current CO_2 emission calculation methods related to aeronautical activities within the LTO cycle, developing a model incorporating data specific to local conditions to estimate CO_2 emission and estimating additional CO_2 emission due to delay and validating the model are the main objectives of this study. The results of the suggested methodology for calculating CO_2 emission were compared with the industry standards and actual operational values. The CO_2 emission of different phases of flight and the CO_2 emission due to delays within the LTO was assessed using the suggested methodology.

The suggested methodology shows the unnecessary fuel burn and emissions according to current practices. The outcomes encourage stakeholders to initiate emission reduction methods. This study can be used as a reference when implementing those reduction methods. The suggested methodology can be applied in any airport which has data and technological constraints. The CO_2 emission from delays at the taxiing phase has a significant influence on local air quality. The taxiing out phase which is the highest contributor to delays within the LTO should be given the most priority when initiating emission reduction methods.

Keywords- CO_2 emission, LTO cycle, taxiing delays, APU, WTC

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List of Abbreviations

AASL	Airports and aviation services Ltd
ACI	Airport Council International
ACA	Airport Carbon Accreditation
ACERT	Airport Carbon and Emissions Reporting Tool
ACRP	Airport Cooperative Research Program
ADS-B	Automatic dependent surveillance-broadcast
AEDT	Aviation Environmental Design Tool
AEM	Advance Emission Model
APU	Auxiliary Power Unit
ATC	Air Traffic Control
BIA	Bandaranaike International Airport
CAEP	Committee on Aviation Environmental Protection
CCD	Climb, Cruise, and Descent
CORSIA	Carbon offsetting and reduction scheme for international aviation
DAMR	Daily Aircraft Movement Record
EASA	European Aviation Safety Agency
EDMS	Emissions and Dispersion Modeling System
EEA	European Environment Agency
EF	Emission Factor
EFPS	Electronic Flight Processing Strips
EIA	Environmental Impact Assessment
FDRs	Flight Data Recorders
GHGs	Greenhouse Gases
GPU	Ground Power Unit
GSE	Ground Support Equipment
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LTO	Landing Take-off
NDCs	Nationally determined contributions
SAGE	System for assessing aviation’s global emissions
SARPs	Standards and Recommended Practices
SDGs	Sustainable Development Goals
TIM	Time-In-Mode
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme

UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WMO	World Meteorological Organization
WTC	Wake Turbulence Category

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1. INTRODUCTION

1.1 Background

Being the safest transport mode [1], the demand for aviation shows a speedy growth due to the rapid globalization and increasing affordability of air travel. The International Air Transport Association (IATA) anticipated that there will be more than 7 billion passengers in 2036 assuming a 3.6% average annual growth rate [2]. Worldwide, aircraft produced 859 million tons of CO_2 in 2017 [3]. It is anticipated that the growth of air travel will triple the aviation contribution of CO_2 emissions between 1990 and 2050 [4].

The aircraft emits CO_2 directly into the higher levels of the atmosphere and it adversely affects the climate [5]. Climate change is a global issue affecting every country with disrupting national economies and all living beings. Changes in weather patterns, extreme weather events, sea-level rise and Greenhouse Gas (GHG) emissions align with climate change becoming environmental disasters.

1.2 GHG Emissions from aviation

GHGs consists of gases which absorb and emit heat and keep the Earth's surface warmer than it is usual [6]. The GHGs are water vapor (H_2O), methane (CH_4), carbon dioxide (CO_2), ozone (O_3) and nitrous oxide (NO_x). GHGs cause ecological, physical and health impacts while disrupting national economies and affecting all living beings in the world. GHGs trigger for extreme weather, changes of glaciers and sea-level, changes in crop growth and disrupted water systems worldwide.

Aircraft use two types of fuels; kerosene and gasoline. Aircraft engines emit H_2O, CO_2, NO_x, SO_x, CO as gases that cause for the GHG emission [17]. However, Other GHG emissions are significantly lower compared to the CO_2 emission of an Aircraft [7]. When the CO_2 emission is 70%, water vapour emission is less than 30% and all other remaining GHGs are less than 1% [8]. The GHG emission depends on the aircraft type, engine type, fuel type, flying altitude and engine load [9].

1.3 Flight cycle

The phases of a flight can be named as a flight cycle. The flight cycle is usually divided into two main cycles by International Civil Aviation Organization (ICAO)[10]. LTO cycle (Landing and Take-off) and CCD cycle (climb, cruise, and descent) are those cycles. LTO consists of all the movements of a flight that takes place below 3000 ft (914.4 m). LTO consists of the pushback, taxi-out, take-off run, take-off, climb-out, final approach, landing and taxi-in phases of flight. According to the ICAO, local air quality is affected during the LTO cycle of an aircraft as emissions are released below 3,000 feet. CCD consists of all the flight movements that take place above 3 000 feet (914.4 m). CCD consists of the climb, cruise and descent phases of flight [7]. Figure 1.1 indicates the LTO cycle and the CCD cycle.

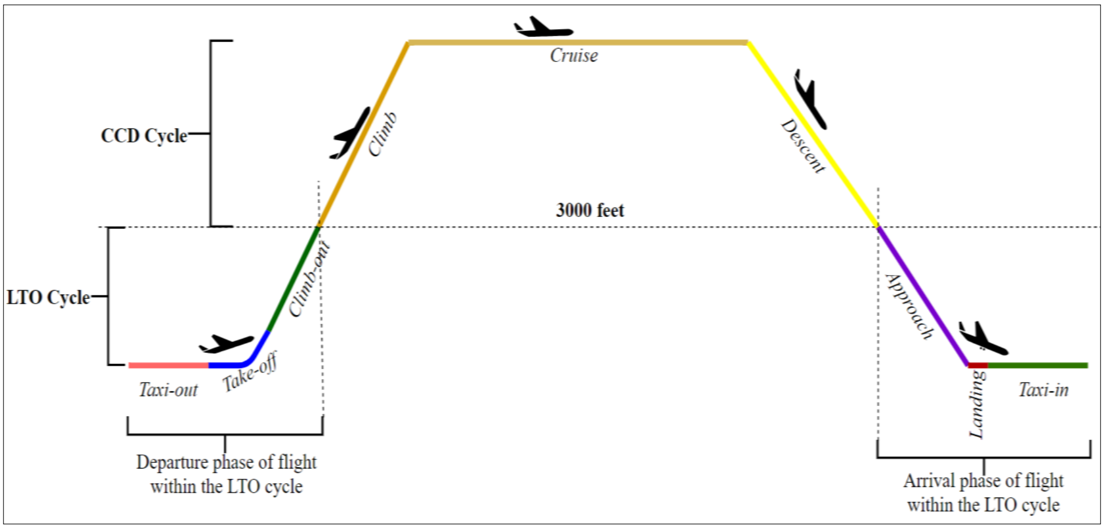


Figure 1.1 : LTO and CCD cycle

1.4 Emission sources of Aviation

The global aviation emission contributes 2% to the total global GHG emission [11] and it includes only the emission from “International Aviation” which refers to the emission from all phases of flight (LTO cycle + CCD cycle) and Auxiliary Power Unit (APU) [12]. Emission from airport operation is not considered under the global aviation emission. However, aircraft emit only 95% of carbon, whereas the airport operation is responsible for the remaining 5% [13] of emission. The emission from the movements of aircraft includes the CCD cycle, LTO cycle and APU. This 5% of emissions from airport operation is ignored even though it affects the local air quality.

1.4.1 Emission sources at airports

Emission sources at the airport were categorized according to the GHG protocol which provides standards and tools to counties for reducing the impact of climate change. According to the GHG protocol, emission sources are categorized into 3 sections. Emission inventories that are owned or controlled by the airport operator fall under the category of scope 1. Emissions from airport power generation facilities, airport fleet vehicles, combustion in boilers, water and waste processing are some of the sources under this category. Scope 2 emission consists of sources that are purchased by the airport operator. The off-site generation of the electricity purchased the supply of heating or cooling can be considered under this category. Scope 3 emission consists of airport activities related to sources that are not owned or controlled by the airport operator. Aircraft emissions and ground transport vehicles that are not owned and controlled by the airport operator and those sources are categorized under scope 3 [7].

Table 1.1 indicates emission sources at the airport according to the scopes [14]. According to Table 1, emission from the LTO cycle and APU which is a part of “International Aviation” be considered under scope 3 since those sources influence the local air quality. In this research, emission from the LTO cycle and the emission from APU operation are evaluated.

Table 1.1: Emission sources at an airport

Vehicles (airside transport, machinery and Ground Support Equipment (GSE))	Scope 1
Buildings (gas/oil/coal)	
Emergency Generator	
Deicing/Glycol	
Fire Training	
Process Emissions (waste, water, refrigerants)	
Electricity purchased	Scope 2
Heat purchased	
Aircraft (LTO cycle)	Scope 3
Aircraft APU	
Aircraft Engine Run-ups	
Deicing/Glycol	
Vehicles (airside transport, machinery and GSE)	
Buildings (gas/oil/coal)	
Electricity purchased	
Heat Purchased	
Emergency Generator	
Fire Training	
Process Emissions (off-site/third party: waste, water)	
Airport Constructions (contractors)	
Public Access	
Tenant Staff/Visitor Vehicles	
Airport Staff Business Travel	
Airport Employee Commuting	

Source: ACI, "ACERT - Environment - Priorities - ACI World." [Online]. Available: https://aci.aero/about-aci/priorities/environment/acert/. [Accessed: 21-Apr-2019]

1.5 International approaches towards Climate Change

1.5.1 United Nations (UN)

The UN which is an intergovernmental organization aims to maintain international peace and security with its 193 member states. Improving the well-being of people is one of the main focuses of the UN and in order to achieve it, the UN promotes sustainable development to improve the quality of life without compromising that of future generations. The UN identified the increasing dangers of climate change and hosts several environmental conventions, secretariats and inter-agency coordinating bodies to resolve the global issue. Those environmental bodies follow different approaches in reducing adverse environmental impact. Figure 1.2 indicates those environmental bodies that tackle climate change by bringing together the environmental community.

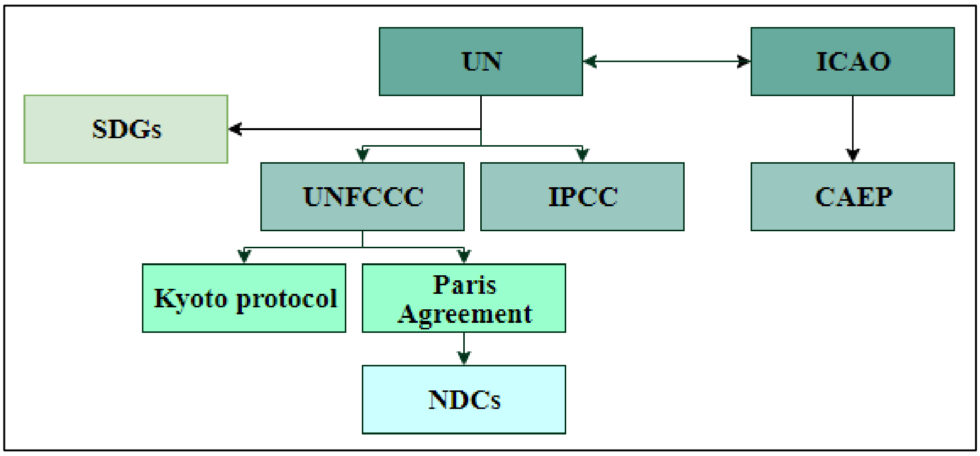


Figure 1.2: International organizations that commit to climate actions

1.5.2 International Civil Aviation Organization

The Convention on International Civil Aviation established the ICAO for coordinating and regulating international air travel. As a specialized agency of the UN, ICAO works with its member states and aviation industry to reach a general agreement on policies and Standards and Recommended Practices (SARPs) related to international civil aviation. SARPs for a safe, efficient, economically and environmentally sustainable civil aviation are set by the ICAO as the regulator of civil aviation. Each member state has to follow SARPs for safer commercial aviation since those are mandatory.

ICAO undertook to find solutions for the GHG emissions of international aviation since it is one of the main causes of climate change. Therefore, the 37th session of the ICAO assembly adopted the goals for reducing emission in 2010 [15].

- A cap on aviation CO_2 emissions from 2020 (carbon neutral growth)
- An average improvement in fuel efficiency of 1.5% per year from 2009 to 2020

- A reduction in CO_2 emissions of 50% by 2050, relative to 2005 levels

These environmental goals are not mandatory and only few aviation bodies voluntarily involve in achieving them. The ICAO adopted technological advances, market-based measures, operational improvements and alternative sustainable fuels as solutions for achieving above goals.

Standards and Recommended Practices

SARPs are technical specifications published by the ICAO in the form of Annexes to the Chicago Convention aiming to assist member states to have a degree of uniformity in regulations, standards, procedures and organization in relation to aviation. SARPS are included in each area of ICAO responsibility within 19 Annexes. Each Annex is specific to a particular subject area. Personnel Licensing, rules of the air, meteorological services, aeronautical charts, units of measurement, operation of aircraft, aircraft nationality and registration marks, airworthiness of aircraft, facilitation, aeronautical telecommunications, air traffic services, search and rescue, aircraft accident and incident investigation, aerodromes, aeronautical information services, environmental protection, security, safe transportation of dangerous goods by Air and safety management are the main subject areas of 19 Annexes.

A few SARPs were recently adopted by the ICAO under the environmental impact of aviation. Annex 16 addresses the environmental protection SARPs related to aviation. The Annex 16 volume I discusses the aircraft noise while volume II discusses the emission of the aircraft engine. ICAO adopted SARPs for aircraft engine certification for NO_x and CO within the LTO cycle in 2008. The ICAO adopted SARP for prevention of intentional aviation fuel venting in 2014 under Annex 16 volume II [10]. The Annex 16 volume III adopted SARPs for the CO_2 emission of airplanes in 2017 [16]. The Annex 16 volume IV adopted SARPs for Carbon offsetting and reduction scheme for international aviation (CORSIA) in 2018 [17]. Figure 1.3 indicates a summary of Annex 16.

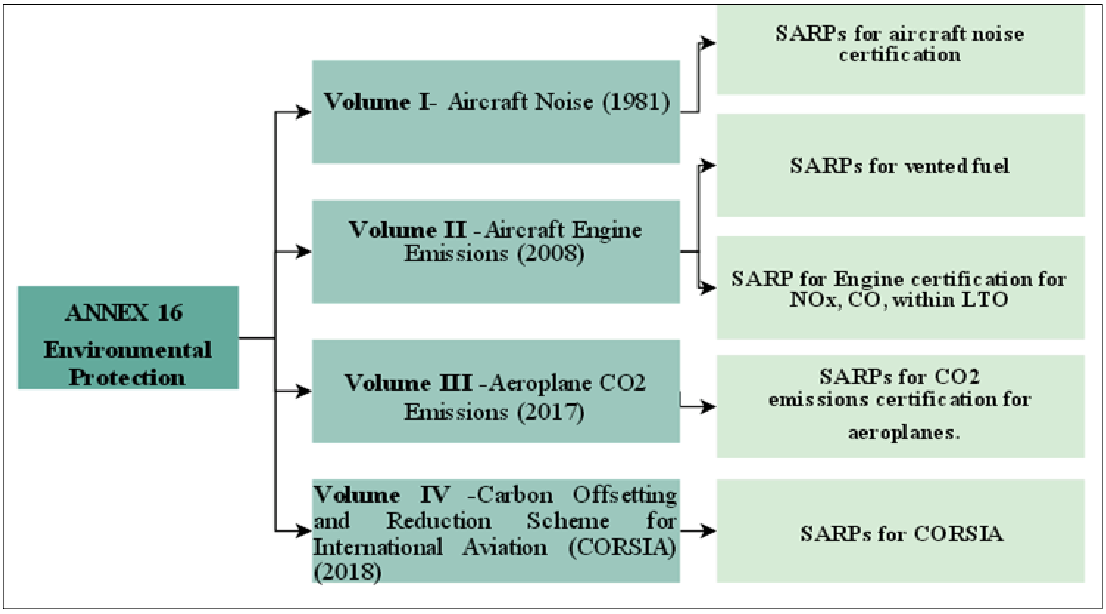


Figure 1.3: SARPs of ANNEX 16

1.5.3 Committee on Aviation Environmental Protection (CAEP)

The CAEP that is one of the technical committees of the ICAO, assists to formulate policies and SARPs related to aircraft noise and emissions. The CAEP develops proposals to minimize environmental impact of aviation. The ICAO reviews and adopts CAEP recommendations, including amendments to the SARPs on Annex 16.

1.5.4 Sustainable Development Goals (SDGs)

In 2015, the UN adopted a set of 17 SDGs to achieve a sustainable future for all the countries [18]. The SDGs concern the social needs including education, health, job opportunities, justice and a range of global issues including poverty, hunger and inequality while tackling environmental protection. The Goals are interconnected and those should be achieved by 2030. ICAO committed to achieving SDGs and ICAO's Strategic Objectives are aligned with 15 of the 17 SDGs [19] as well as 11 out of 15 goals are aligned with the environment. The ICAO is committed to cope with countries and other UN bodies to assist in achieving SDGs. Figure 1.4 indicates the SDGs that are contributed by the ICAO environment.

Figure 1.4: SDGs that is supported by the ICAO environment
Source: ICAO, "ICAO and the United Nations Sustainable Development Goals." [Online]. Available: https://www.icao.int/about-icao/aviation-development/pages/sdg.aspx. [Accessed: 04-Mar-2019].

2. Zero Hunger

The ICAO supports for this goal by the production of sustainable aviation fuels that avoid competition with food supply. The sustainable aviation fuels do not support climate change, extreme weather, drought, flooding and that increase productivity and production of food.

3. Good health and well-being

ICAO supports this goal by limiting the impact of noise and emission from international civil aviation operation on local air quality around airports and public health by establishing SARPs.

4. Quality Education

ICAO supports this goal by providing quality education. ICAO conducts training seminars and symposia focused on the exchange of the latest knowledge on environmental subjects. This includes training programs on action plans, online tutorials to reduce emissions from international civil aviation.

7. Affordable and Clean Energy

The focus in this SDG is to develop sustainable aviation fuels and to deploy renewable energy at airports. The sustainable alternative fuels can be up to 80% less carbon-intensive than jet fuel[20]. ICAO supports this goal by encouraging to use clean and renewable energy sources for aviation. ICAO created an online platform to provide a continuously updated database of activities and developments in the field of alternative aviation fuels. ICAO promotes energy innovation such as solar power and shares information and best practices amongst stakeholders on clean energy to reduce the impact of airport operations on the environment by conducting international conferences.

8. Decent Work and Economic Growth

ICAO supports green growth to achieve sustainable development for the aviation sector. ICAO adopts green economy initiatives such as green technologies and clean energy (aviation biofuels). Green economic growth for the aviation sector has the potential to generate significant social benefits, including safe and secure working environments and sustainable tourism.

9. Industry Innovation and Infrastructure

ICAO supports to identify the potential impacts of climate change on aircraft operations and related infrastructure. ICAO supports this goal by adopting measures to address the impacts on the environment. The aviation sector develops new technology for better air traffic management and builds significant urban infrastructure such as airports. Currently, new generation of aircraft is 15-20% more fuel efficient than the previous generation [21].

11. Sustainable Cities and Communities

ICAO supports this goal by guiding on eco-friendly airports. ICAO develops and updates SARPs which addresses the local air quality. ICAO supports sustainable land use planning at the national level by establishing positive environmental links among regions. The adverse environmental impacts of cities are reduced through improvements in local air quality and waste management.

12. Responsible Consumption and Production

ICAO supports this goal by evaluating policies for aircraft recycling. ICAO promotes waste management in order to prevent air, water and soil pollution. ICAO's environmental SARPs contribute to enhance sustainable consumption and production patterns.

13. Climate Action

ICAO provides policies, Standards, guidance, goals and tools, aiming to reduce the emissions from aircraft operation. ICAO recently adopted the first CO_2 emissions Standard for aircraft (2017). However, the standard will only mandate to aircraft designs from 2020. It is expected by the ICAO that technical and operational improvements will minimize fuel consumption and CO_2 emissions. ICAO adopts new SARPs for CORSIA under Annex 16. It will define methodologies related to monitoring, reporting, verification of CO_2 emissions and carbon credits.

15. Life on Land

ICAO supports the development and deployment of sustainable aviation fuels which will contribute to land-use patterns and terrestrial ecosystems, such as forests. The sustainable forest management will secure life on land.

17. Partnerships for the Goals

ICAO supports this goal by assisting member states to integrate and implement CO_2 emission reduction measures. ICAO contributes to the methodologies established to achieve the SDGs exploring opportunities for financing green aviation initiatives and adopting strategic partnerships with the World Health Organization (WHO), International Maritime Organization (IMO), International Renewable Energy Agency (IRENA) and World Meteorological Organization (WMO). ICAO cooperates with private-sector stakeholders to reduce adverse environmental impact from international aircraft operation [22].

1.5.5 Intergovernmental Panel on Climate Change (IPCC)

The United Nations Environment Programme (UNEP) and the WMO created the IPCC in order to provide scientific evaluation related to climate change to various governments. Those evaluations are used by the governments as the policymakers. Developing methodological guidelines for national GHG inventories, the IPCC act as an intergovernmental body. The IPCC does not establish regulations but does assessments to identify the scientific involvements in different areas where climate change can be expected [23].

1.5.6 United Nations Framework Convention on Climate Change (UNFCCC)

The United Nations Conference on Environment and Development (UNCED) constituted an international treaty, UNFCCC in 1992. The aims of the treaty are to achieve a stable GHG concentration while maintaining it at a lower level which has a minimum potential to be an interference to the global climate. The Treaty is not legally binding and it includes provisions for updates to the Kyoto Protocol that sets mandatory limits on GHG emissions. The UNFCCC considers the domestic(ground-based) sources that emit GHGs and emission from airport operation and domestic aircraft are addressed[24][9].

1.5.7 Kyoto Protocol

Kyoto Protocol which sets internationally binding targets to its members is an international treaty linked to the UNFCCC. Assigning mandatory targets for reducing GHG emissions to member states, the Kyoto Protocol monitors annual emission inventories of member states. The Kyoto Protocol committed to reducing emissions of CO_2, CH_4, N_2O, HFC, PFC and SF_6 from the domestic sources. The Kyoto Protocol excludes emissions from “International Aviation” which refers to the emission from all phases of flight and APU[12]. However, 2% of aviation emission includes only the emission from international aviation.

1.5.8 The Paris Agreement

The Paris Agreement also strongly links to UNFCCC. With the constitution of the Paris Agreement, all nations brought into a common platform where ambitious efforts are undertaken to suppress climate change. The Paris Agreement aims to strengthen the global action towards climate change by setting goals. The Paris Agreement also considers the domestic sources that emit GHGs and emission from airport operation and domestic aircraft are addressed [25].

1.5.9 Nationally determined contributions (NDCs)

According to the Paris Agreement, all nations have to put forward their targets and efforts through NDCs. Nations have to gradually strengthen their efforts and have to report regularly. Each country prepares its own targets and efforts under NDCs to reduce the national emission of the country. Each country is required to calculate its national emission and communicate it to the Paris Agreement. Maintaining successive NDCs is another target of the country. Each party have to set domestic targets and efforts under five categories. Energy, transport, forestry, waste and industry are those categories and national emission under those categories have to be calculated [26]. Whilst emissions from domestic aviation fall under the scope the Paris Agreement and the UNFCCC, ICAO was authorized to address GHG emission from international aviation [26].

NDCs Sri Lanka set the following targets under the aviation sector in order to reduce GHG emissions[27]. Numerical targets are not set due unavailability of historical data related to emission calculation.

- Identify the current state of GHG emissions from Sri Lankan operators in both international and domestic operators
- Forecast future emissions from the operators
- Identify GHG mitigations methods
- Identify mechanisms and resources for the implementation of mitigation methods

1.6 Importance of evaluating GHG emission in Sri Lankan aviation Sector

All the countries are currently focusing on achieving SDGs with the support of United Nations Development Programme (UNDP). Even though this is not a mandatory requirement as a member state of the UN, Sri Lanka needs to take steps to achieve those goals. Currently under the UNFCCC, Sri Lanka needs to report on their level of national emission as well as targets through NDCs. Reporting to the Paris Agreement is also not mandatory, but it is a responsibility as a member state.

Emission of domestic flights and emission of airport are needed to report to the Paris Agreement. Even though emission from the LTO cycle of international flights are not required to report to any international organization by now, when achieving the SDGs every emission source is needed to evaluate to reduce its impact. The involvement of all the nations is required for achieving the SDGs to leave a better planet for future. Therefore, working to achieve SDGs is a responsibility of all the nations.

1.7 Methodologies available to calculate GHG emission of Aviation

The IPCC has developed and revised over time the guidelines for calculating GHG from emission inventories with the updated technologies.

1.7.1 IPCC recommended method

IPCC recommended the 3 Tier method to calculate aviation emissions in IPCC 2006 Guidelines [28]. According to the Tier 1 (default method), the IPCC supports any country to implement this method, including emission factors and guidance on how to obtain data. The Tier 2 uses the same mathematical structure of Tier 1 and however, member states need to obtain country specific data according to their national circumstances. Tier 3 method is more complex and involves in models, land use data.

1.7.2 Airport Council International (ACI)

ACI is the only global trade representative of all the airports. As the representative, ACI handles airports interests with international organizations and governments while supporting the development of standards, policies and recommended practices for airports.

The ACI has developed a methodology for calculating GHG emissions from aviation inventory following the methodology of IPCC. Even though aircraft face a number of flight phases like taxi-out, pushback, take-off run, take-off, and climb-out, climb, cruise, descent and taxi-in ACI has used LTO and CCD categorization for calculating emission levels. Emission from different phases of flight has not been recognized in this method.

1.7.3 Airport Cooperative Research Program (ACRP) Report 11

This is a guidebook that supports for preparing airport emission inventories in order to assist airport operators. This guidebook assists in identifying and quantifying airport contributions to GHG emissions. The quantification approaches for emissions sources are provided. ACRP suggests calculating the emission of aircraft following IPCC guidelines for 3 tiers method.

Tier 1 uses fuel sales data of a particular airport to calculate total emissions for all its departures. Aggregate emission from departure flight is calculated without segregating into different phases. It is assumed that fuel sales data is equal to the fuel consumed by each flight. Tier 2 also uses fuel sales data and uses methods to separately calculate emissions from the LTO and CCD cycles. This method assists to identify emission that affects local air quality by calculating emission from the LTO cycle separately. This method supports for calculating emission from the APU. Tier 3 does not use fuel sales data and it uses sophisticated models and software for calculating fuel consumption by departure flight. Then the fuel consumption is converted to CO_2 emission. It is assumed that 1 kg of jet fuel can generate 3.16 kg of CO_2 [8].

1.7.4 CORSIA

IATA as the trade association for the world’s airlines, is focused on developing environmental policies to achieve sustainable air transport. CORSIA is one of the main environmental policies of IATA. The CORSIA as a global scheme addresses the increase in total CO_2 emissions from international aviation above year 2020 levels. All the airlines are required to report their CO_2 emission levels annually from 2019 onwards. It is expected to mitigate CO_2 emission from international aviation by following the CORSIA. ICAO adopted the SARPs for CORSIA as Annex 16, volume IV on 27th June 2018 [29].

1.7.5 Airport Carbon Accreditation (ACA)

ACA is an independent program that manages the CO_2 of the airport with 4 levels of certification. ACA is owned by ACI EUROPE and it annually enforces the accreditation criteria for airports. The administration of the ACA is managed by an Advisory Board. The ACA follows a unique framework and tool for measuring carbon at airports. Some airports voluntarily follow this program to become a carbon neutral airport. Carbon emission within the airport perimeter is measured by this program [30].

ACA follows the categorization of emission inventory recommended by the greenhouse gas protocol[14]. ACA calculates the emission of each airport source separately according to the scope categorization. Emission is generally calculated by multiplying the relevant emission factor with activity data. However, aggregate emission of the LTO cycle is calculated without segregating to its phases.

1.7.6 Excess emission due to aircraft delays

The demand for air transport shows rapid growth due to globalization and increasing affordability for air travel. It was recorded by ICAO that 4.1 billion passengers used scheduled flights in 2017. This figure indicated 7.1% increase over the year 2016 [31]. The annual growth rate of air passengers was forecasted at 6.2% in the Asian Pacific region for the year 2015 to 2040 [32].

Currently, many Asian hub airports are operated with over capacity. Other Asian airports are starting to experience capacity strains. As a consequence of this infrastructure constraint, aircraft congestion delays, long queues for take-off and cycling of aircraft in stacks prior to landing are experiencing. In 2013, only 57% of departures from Asian airports were on time [33].

The delay of an aircraft at ground operation can be defined as the additional waiting time compared to the unimpeded time when there is no interference. Additional waiting time causes for additional fuel consumption as well as more emissions. Whenever the flight movements are greater than airfield capacity, flight delays at the taxiing phase can be expected. Airfield capacity can vary due to various inefficiencies in capacity utilization. In a typical airport, the primary bottleneck is the capacity constrained runway system. The delay of an aircraft carries a ripple effect. When an aircraft delays it affects to the other aircraft in a queue of landing or taking off. A flight delay can carry a huge impact on the number of stakeholders such as airport operators, tower controllers, ground controllers, passengers, connecting flights etc.

1.8 Research Gap

In the Sri Lankan context, NDCs of Sri Lanka have been prepared in order to reduce the emission levels. Under the transport sector, NDCs of Sri Lanka should address all modes of transport. However, emission from aviation is ignored due to the unavailability of data to calculate baseline emissions from the Sri Lankan aviation sector[34]. NDCs need to calculate emissions from the airport operation and emission from the domestic flights and their APU emission. Emission from the international flights is not accounted under NDCs[35].

Current methodologies to calculate the aviation emission in the LTO cycle fails to differentiate the amount of GHG caused to delays within different phases. Segregating delay induced GHG levels is important to initiate as well as justify emission reduction methods or investments. Airport capacity issues directly influence delays and ensuing GHG emission in all the phases of aircraft operation. It is important to focus on the excess level of emission in order to determine effective ways of emission reduction.

Therefore, an alternative methodology is required to evaluate the emission of different phases of flight within the LTO cycle to achieve the following objectives.

- Less data intensive and ability to utilize commonly available data on aircraft activity for CO_2 emission estimation
- Ability to take into account the conditions specific to individual airport (congestion and other site-specific factors influencing time in mode) when estimating CO_2 emission levels
- Ability to evaluate emissions levels separately (disaggregate) within each phase

Current methodologies for calculating emission within the LTO cycle fails to differentiate the amount of emission caused due to delays. Operational delays in aircraft movement within the LTO cycle is one of the major contributors of excessive emission and its contribution will be increased due to higher demand in the future.

Emission from international or domestic flights within the LTO cycle and the emission from APU are important for assessing impacts to local air quality due to airport operations. No previous attempt has been made in the Sri Lankan context to explore the methods of estimating GHG levels due to aviation in general. The importance of airport GHG inventory is more specific in the local context as it directly affects the air quality of the airport vicinity. Extremely limited attention in terms of research has been given in the Sri Lankan context to evaluate GHG due to the activities of the airport operations. Except the research carried out on GHG due to airport operation[36], no published research or reports on airport related GHG emission at BIA is found. The specific gap addressed by this research is evaluating the GHG emission related aircraft within the LTO cycle. Using currently available industry guidelines or methodologies for evaluating the emission from the LTO cycle in the Sri Lankan context has significant limitations such as:

1. Unavailability of relevant operational data specific to the LTO cycle (for using IPCC Tier 2 and 3 methods)
2. ICAO specified “time in phase” estimates for estimating fuel consumption at different phases of the LTO cycle is inconsistent with local standards. Such

industry-wide standards have been found to overestimate actual specific to local conditions [9].

Segregating delay induced GHG levels is important to initiate as well as justify emission reduction methods or investments. Emission from the APU of aircraft was ignored from the available literature.

1.9 Research Scope

According to the ICAO, local air quality is affected during the LTO cycle of an aircraft as emissions are released below 3,000 feet [37]. Therefore, the different phases of flight within the LTO cycle and the aircraft APU operation were selected in this study due to its influence to the local air quality. The departure flight includes different phases such as waiting at the gate, pushback, taxiing out, waiting at the runway entrance, take-off roll, take-off and climb within the LTO cycle. The arrival flight includes different phases such as approach, touchdown, taxiing in and parking at the bay. Aircraft operates its engines in most phases of flight while APU serves as an additional energy source. APU is normally used to start one of the main engines of a flight. The APU generates enough power to operate onboard lighting, galley electrics and cockpit avionics when the aircraft is parked at the bay. The APU is shut down before takeoff and switched on when the aircraft clears the runway after landing. Figure 1.5 depicts the phases of the departure flight within the LTO cycle. Figure 1.6 depicts the phases of arrival flights within the LTO cycle.

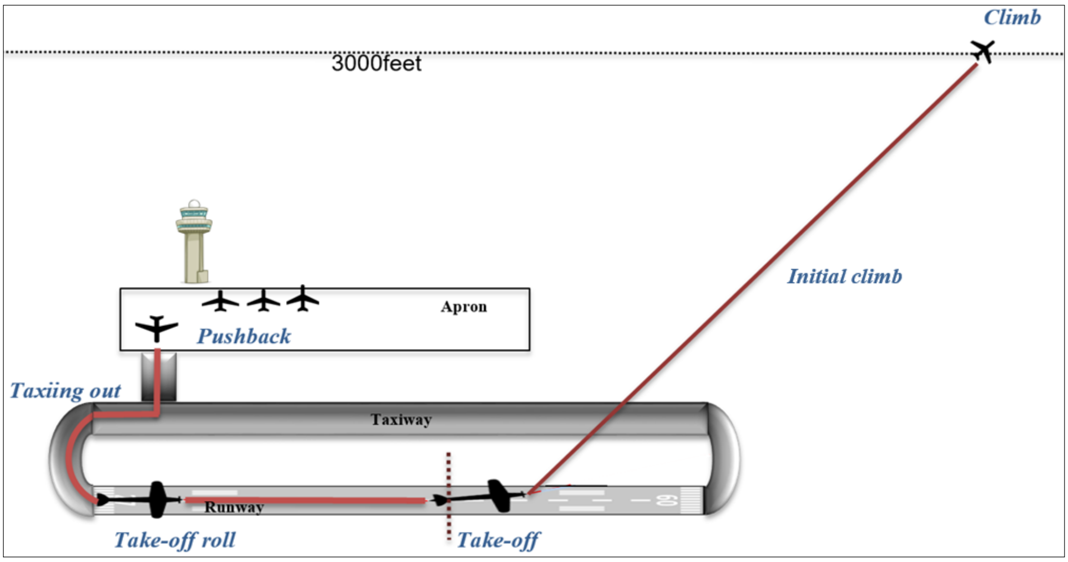


Figure 1.5: Phases of departure flight within the LTO cycle

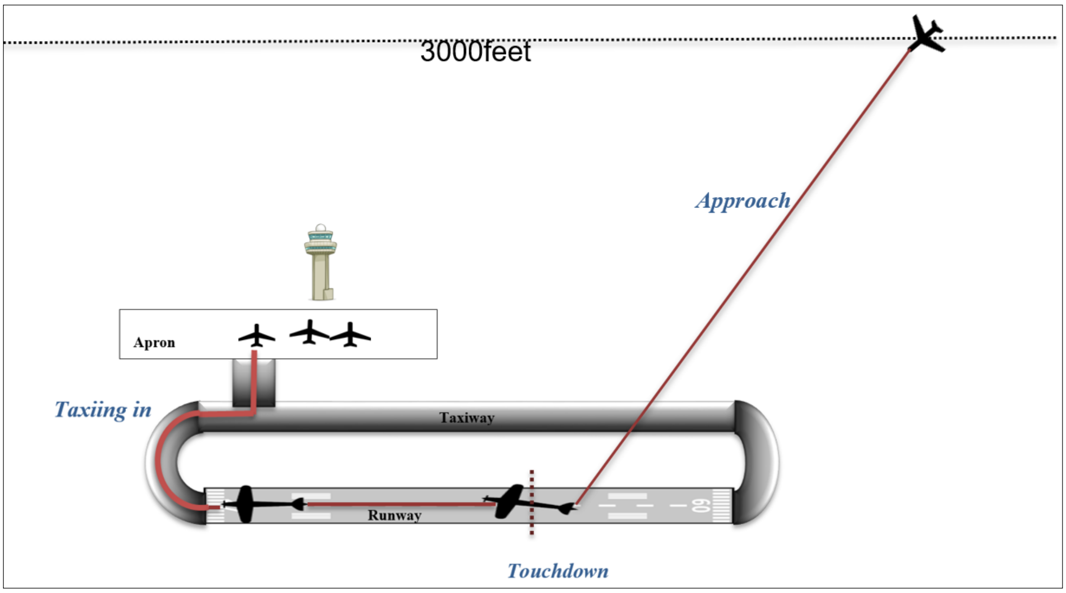


Figure 1.6: Phases of arrival flight within the LTO cycle

1.10 Research Objectives

1. To review current CO_2 emission calculation methods related to aeronautical activities within the LTO cycle
2. Develop a model for evaluating CO_2 emission within the LTO cycle incorporating data specific to local conditions
3. Evaluate the model with actual operational data.

1.11 Significance of the research

Making climate change initiatives, implementing environmental management and sustainability programs, disclosing project effects and making future regulations are some of the reasons to maintain an emission inventory as a country.

An emission inventory can be the reference for the evaluation of work performed at reducing the GHG effect and monitoring progress over time. Policymakers need emission inventories to track trend patterns of emission and to develop policies. In general, the results of an inventory represent the information needed to identify which sources have to be controlled to reduce the emission.

The research focuses on the evaluation of CO_2 emission within the LTO cycle at BIA since the local air quality is affected at this stage when emissions are released below 3,000 feet. The public awareness of local air quality around the airport is also growing by becoming an additional constraint to the airport operators. As a consequence, accurate air quality studies in airport are becoming more important. Assessing the emission level at BIA has not been conducted before. By assessing the emission level of aircraft at BIA, the current state of emission level can be identified, and it can be used as a future reference. Methodologies for emission reduction can be initiated when the current state is identified. However small to medium size capacity constrained airports in most developing countries such as Sri Lanka lack necessary operational data for accurately estimating CO_2 emission attributable to LTO cycle. Less data intensive aggregate methods using broadly defined international parameters tend to overestimate actual levels. Having an appropriate methodology to calculate emission at an international airport using locally available data is an important significance of this study. The proposed methodology of this research can be applied to any other airport with similar conditions.

1.12 Layout of the thesis

This thesis is organized as follows. Chapter One contains an introduction and gives background of the study. Chapter Two presents the review of literature relevant to this research. The chapter discusses literature relating to CO_2 emission calculation methods and tools used by the international organizations. Chapter Three provides a methodology followed to evaluate CO_2 emission at BIA by considering local standards. Chapter Four provides analysis and the results obtained by following the methodology recommended from Chapter three. Chapter Five, the final chapter, presents the conclusions and recommendations.

2. LITERATURE REVIEW

2.1 Emission calculation methods

2.1.1 Basic method of calculating emission

The most common approach for calculating GHG emissions of any source is based on estimating or obtaining fuel use information or an appropriate indicator of the activity level. Emission is generally calculated by multiplying the relevant emission factor with activity data given by Equation 01.

$$\mathrm{E} = \mathrm{A} \times \mathrm{EF} \qquad (01)$$

Where: E - Emission (kg or tons)

A – Activity level (ex: fuel used (kg), electricity used (kW))

EF- Emission Factor per unit of activity expressed by A.

Emission factors should be obtained from reliable sources such as IPCC, Environmental Impact Assessment (EIA), and United States Environmental Protection Agency (USEPA) etc. [8].

The most common approach to calculate GHG emissions of aircraft within the LTO cycle is performed through the application of specific emission factors, relating to the condition of the engine thrust derived from experiments for different models of engines[38]. The IPCC has developed and revised over time guidelines for greenhouse gas inventories and calculation approaches with technological advancements[7].

2.1.2 Emission calculation methods of ICAO

ICAO suggests standard methods to calculate GHG emission of aircraft. The Simple Approach (option A) is a basic method used for calculating CO_2 emission using the number of LTO cycles. The aggregate CO_2 emission within the LTO is calculated using Equation 02.

$$\text{Emission}_{\,(\mathrm{CO_2})}\ (\mathrm{kg}) \\ = \sum \text{No: of LTO cycles of aircraft } \times \text{EF (kg per aircraft)} \qquad (02)$$

This equation does not account for specific engine types, operational modes (taxiing, take-off, climb, approach) because it assumes that the conditions under study are the same[39].

There is another version of the simple approach (option B) where aircraft time-in-mode (TIM) is considered by recognizing the engine type. The engine type provides more accurate EF for calculation. However, the ICAO recommended default TIM values are too broad given for specific airport conditions and likely to overestimation of total aircraft emissions across the entire LTO cycle. ICAO default TIM values are not based on engine type, airport configuration and operation conditions[40]. The For an illustration, ICAO suggested taxiing time is 26 minutes and typically, taxiing time depends on various factors such as runway capacity, runway, taxiway and apron configuration, wind direction, weather and inefficiencies on Air Traffic Control (ATC). Thus, this average value for the taxiing is not accurate for all the airports. The fuel flow and EF are taken from ICAO default values. This method also estimates the total emission of the LTO cycle and each different phases of flight have to be calculated separately. Another limitation of the above method is that both taxiing-in and taxiing-out are accounted for as a single phase. Thus, this method does not support to identify CO_2 emission of taxiing in and out separately. The Equation 03 is used in this approach to estimate emission level[39].

$$\mathrm{E_j} = \sum \mathrm{TIM_{jk}} \times \mathrm{FF_{jk}} \times \mathrm{EF_{jk}} \times \mathrm{N_j} \qquad (03)$$

Where;

E_j = total emissions of CO_2 produced by aircraft type j for one LTO cycle (kg)

EF_{jk} = emission factor (for CO_2) in mode k (take-off, climb-out, idle/taxiing and approach) for aircraft type j (kg of CO_2 /kg of fuel)

FF_{jk} = fuel flow for mode k for aircraft type j (kg/s)

TIM_{jk} = time-in-mode for mode k for aircraft type j (s)

N_j = number of engines used on aircraft type j.

Even though the above method calculates the emission under specific stages it uses default ICAO LTO cycle engine thrust settings. However, the default engine thrust indicates the maximum thrust levels under a specific phase and that method provides an overestimation of emission. For an illustration, an aircraft may be permitted to reduce the thrust required for take-off from 100% Foo to a lower setting no less than 75% by considering other safety factors[41][42]. Since an aircraft is at its maximum engine thrust at the phase of take-off, it is a huge cost to the airline due to high fuel consumption. Therefore, some airlines do not use the maximum engine thrust required under different phases in order to save the fuel. The default engine thrust setting according to the phases of flight are indicated in Table 2.1.

Table 2.1: ICAO standards for TIM

Operating mode	Time in operating mode(minutes)	Thrust setting
Take-off	0.7	100 % Foo
Climb-out	2.2	85 % Foo
Approach-landing	4	30 % Foo
Taxiing	26	7 % Foo

Source: M. Winther *et al.*, *EMEP/EEA air pollutant emission inventory guidebook 2016*, no. July. 2017

Foo is the rated output which indicates the maximum engine thrust available for taking-off of the aircraft under normal operating conditions at International Standard Atmosphere sea level static conditions[43]. However, this methodology overestimates the CO_2 emission under different flight phases by using the default engine thrust settings. TIM were calculated in Zurich Airport using Emissions and Dispersion Modeling System (EDMS) methodology and those values deviates from ICAO value for TIM [44]. Therefore, ICAO values are not always accurate for each airport.

2.1.3 Emission calculation methods recommended by IPCC

Table 2.2 indicates the summary of the 3 methods/ Tiers with required data.

Table 2.2: IPCC 3 Tier method

Tier	Data and tools required
Tier 1	Average fleet mix (average aircraft EFs), No: of LTO cycle, fuel sales
Tier 2	Aircraft-specific LTO EFs, No: of LTO cycle, fuel sales
Tier 3	Aircraft type, flight distance, EUROCONTROL Advance Emission Model(AEM)/ FAA Aviation Environmental Design Tool

Tier 1

To estimate the total emissions of CO_2 from all the phases of aircraft, the Tier 1 methodology is sufficient since the total emission of CO_2 depends on the fuel consumed only and not on the technology[28]. Tier 1 approach depends on the aircraft fuel sales data which refers to the gallons or pounds of fuel supplied at an airport. The total fuel sales data is available from the fuel suppliers at the airport. That data can then be converted to CO_2 emissions. That conversion indicates in Equation 04.

$$E(kg) = \mathrm{AR}_{\text{fuel consumption}}(\mathrm{kg}) \times \mathrm{EF}\left(\frac{\text{kg of CO2}}{\text{kg of fuel}}\right) \tag{04}$$

Where:
E = the annual emission from the LTO and CCD phases.
AR fuel consumption = activity rate by fuel sales data from the airport
EF = emission factor.

By using fuel sales data, double counting of fuel usage is prevented at each airport since only the fuel issued is considered for the calculation. However this method does not account for ‘fuel tankering’ since that data are not publicly available[8]. ‘Fuel tankering’ is a practice of most airlines that they purchase more fuel than necessary to fly in order to achieve an economic advantage by purchasing fuel for lower costs in certain regions. Typically, all the aircraft carry additional fuel which is sufficient to fly to an alternate airport in case of emergency. Therefore, by using fuel sales data, the total emission from the departure flights are overestimated in this tier method.

Tier 2

When estimating the total emissions of CO_2, it may be appropriate and accurate to consider the detailed aircraft activity using Tier 2. This approach can be applied if the information on LTOs per aircraft type is available [28].

$$E(kg) = \sum_{Aircraft\ type} AR_{fuel\ consumption}(kg) \times EF\left(\frac{\text{kg of CO2}}{\text{kg of fuel}}\right) \tag{05}$$

E = Annual emission for each of the LTO and CCD phases,
AR= activity rate by fuel consumption for each of the flight cycle (CCD, LTO) and flight types,
EF = emission factor for the corresponding flight type.

Tier 2 uses the same fuel sales data as in Tier 1, but improving the results by calculating LTO emissions separately with applying the LTO specific data of a flight. After calculating the emission of the LTO cycle, the remaining emission according to the Tier 1 is considered as the emission of the CCD cycle. Equation 06 indicates emission of the CCD cycle.

$$\text{Emission}_{(\text{CCD})} = \text{Total Emission}_{(\text{Tier 1})} - \text{Emission}_{(\text{LTO})} \qquad (06)$$

Emission of the APU is not recognized separately and it is considered as a part of CCD emission. AEDT/EDMS of FAA can be used to estimate fuel consumption during the LTO cycle and that consumption can be converted to CO_2 emission with an appropriate emission factor. Aviation Environmental Design Tool (AEDT)/EDMS is able to report the fuel consumption by each aircraft type. The FAA and the (United States Air Force) USAF identified the need to record and analyze air quality conditions at and around airports and started to develop computer programs as a solution for this. EDMS was introduced after many programs by the FAA. In EDMS, the LTO cycle consists of six phases such as approach, taxi-in, startup, taxi-out, takeoff and climb out while the CCD cycle consists of approach, takeoff and climb out. However the EDMS considers the total number of LTO cycles occurring over a year rather than actual TIM [44].

When using Tier 2 method, fuel issued for aircraft is needed for emission calculation assuming that all the issued fuel is burnt within one cycle. However, each aircraft carries extra fuel so that emission is overestimated by using issued fuel instead of actual burn fuel. In this method only the CCD emission is overestimated since the emission of LTO is based on aircraft specific data.

The main difficulty in using Tier 1 and Tier 2 is to get the correct data on fuel used. The recorded statistics in most countries only give data on the fuel supply for aviation, without segregating it between domestic and international as required for evaluating emissions. The IPCC Guidelines do not give any advice on how to obtain these data as required[9].

In Tier 2 methodology, the aggregate EFs and fuel use factors are based on the fuel use of average aircraft. The average aircraft can be different in a particular country and the estimated fuel use as well as the emission could be over or underestimated.

IPCC recommended values for average aircraft depicted in Table 2.3. The domestic LTO cycle includes A320, Boeing 727, Boeing 737, Mc Donald Douglas DC9 and MD80. The international LTO cycle includes A300, Boeing B767, B747 and McDonald Douglas DC10. The default aircraft are quite large and will overestimate LTO emissions in most countries [9].

Table 2.3: Default EFs and Fuel consumption for aircraft

	Fuel	CO_2 EF
Domestic LTO(kg/LTO) –average fleet	850	2680
International LTO(kg/LTO) –average fleet	2500	7900

Source: IPCC, "IPCC Guidelines on National Greenhouse Gas Inventories, Reference Manual," 1996.

Tier 3

Tier 3 does not rely on the fuel sales data and it uses sophisticated models to predict fuel usage at the LTO cycle and CCD cycle separately. AEDT/ System for assessing aviation's global emissions (SAGE) could be used for in this Tier 3 and information about the aircraft fleet, flight schedules, trajectories, and aircraft performance are used for calculating fuel consumption at different phases. Currently, AEDT/ SAGE which is a research tool and is restricted to the general public[8].

Tier 1 and 2 do not support to calculate the emission of APU separately. Since the fuel sales data is used in these methods, emission of APU is included as a part of the aggregate emissions of a flight. Tier 3 can calculate emission of APU since it uses extensive information to identify the fuel consumption accurately in the LTO cycle and CCD cycle.

Emission of APU

By using all 3 methods, IPCC suggests to calculate the emission of APU. Both Tier1 and 2 includes the emission of APU as a part of other emission since both methods use fuel sales data. From Tier 3 emission of the LTO and CCD cycles can be separately identified and it does not include the emission of APU. Therefore, the aggregate emission of the LTO and CCD cycle (Tier 3) is subtracted from the aggregate emission from Tier 1 or 2 in order to obtain the emission of APU.

2.1.4 Emission calculation methods followed by European Airports

European Environment Agency (EEA) has published air pollutant emission inventory guidebook for reducing GHG emissions from European aviation industry. This guidebook follows the Tier methods with some additions. EEA suggests to separate the emission of international and domestic flights under the Tier methods. The main issue lies in the fuel distribution between domestic and international flights.

Under the Tier 2 method, EEA provides the LTO fuel consumption and emission factors according to the aircraft type. In this method, the fuel consumptions at the LTO are based on the standard ICAO taxi times. The standard ICAO taxiing time which is 26 minutes and these may significantly differ from average taxi times at European airports[45]. EEA maintains a spreadsheet to support this emission calculation by providing the fuel used and emissions corresponding to the LTO phase according to the aircraft type.

The Tier 3 method may be used to get an independent estimate of fuel and aggregate CO_2 emissions from aircraft movements. More accurate emission calculation can be expected from Tier 3 as it uses advanced tools. The Tier 3 methodology is based on actual flight movement data and Tier 3A uses origin and destination (OD) data while Tier 3B uses full flight trajectory information. The Tier 3A methodology considers that the quantity of emissions generated varies between phases of flight and fuel burn is related to flight distance. The Tier 3B methodology calculates fuel burnt and emissions throughout the full trajectory of each flight using aerodynamic performance of the aircraft and engine. The Tier 3B needs sophisticated computer models to address the performance and trajectory variables[45].

EEA guidelines neglected some sources where emission occurs and influence the local air quality. Emissions from the start-up of engines and emission from the APU are not accounted due to lack of recorded data. Furthermore, these are not included in the LTO cycle. This emission may have an impact on air quality in the vicinity of airports [45].

2.1.5 Other methods of emission calculation within LTO

Chengwei LU (2018), suggested a method to calculate emission within the LTO cycle. In this approach, the data required by the calculation of LTO emissions are flight NO:, information on flight arriving, leaving and take-off times. Equation 07 is used for estimating the emission of LTO[46].

$$\mathrm{E(kg)} = 365 \times \sum (\mathrm{LTO_i} \times \mathrm{EF_i}\ (\frac{\mathrm{kg}}{\mathrm{LTO}}))\ \times 10^{-3} \tag{07}$$

E refers to the annual emission, $\mathrm{LTO_i}$ refers to the daily average number of LTO of aircraft i and $\mathrm{EF_i}$ refers to the emission factor of aircraft type i. This approach calculates the amount of emission by using the LTO data of each type of aircraft with corresponding emission factors.

In this approach annual emission is calculated without considering emission at different phases of LTO. In order to identify the emission reduction methods, the current emission at different phases should be identified separately. In this approach, emission of APU which is also ignored has a significant impact on local air quality.

Charles Walker(2017) found new methodology to improve the accuracy of emission calculation in aviation industry[47]. With technological advancement, electronic flight processing strips (EFPS) were introduced to the air traffic controllers. The EFPS database records time of pushback, time on hold, and the actual time of departure/arrival, time on-stand to 1-second precision. However, with the use of flight date and time meteorological parameters on emission was also considered in this method. Thus, emission at different flight phases can be separately calculated more accurately. CO_2 is not a function of the engine type but is a constant with 3.15kg per 1 kg of fuel. Therefore, the CO_2 emissions are calculated simply by multiplying the calculated fuel burn by that emissions index[47]. However, the application of this methodology is limited by availability of EFPS data in most airports.

Yashovardhan S.(2014) found new methodology[48] which uses data that are received from Flight Data Recorders (FDRs) were used to estimate the operational values of TIM, fuel burn and emissions produced during the LTO cycle. These operational values are statistically compared with the values of ICAO Engine Exhaust Emissions Databank. It is mostly identified that the operational values differ from the ICAO values in a statistically significant manner. The ICAO databank is found to typically overestimate the values of LTO cycle fuel burn and emissions.

The FDR is the most accurate, onboard operational data source of an aircraft. Moreover, it can account for the effects of nonphysical factors on engine performance, and also estimate the variability in performance parameters. Parameters used in this approach include true airspeed, ground speed and flight Mach number, trajectory information on pressure altitude, latitude, longitude, gross aircraft mass, fuel flow rates, engine spool speeds, combustor pressure, exhaust gas temperature, and engine pressure ratio. The ICAO databank used standard values of thrust settings and times in mode to certify engine fuel burn and emissions. Since the ICAO databank reports values at standard sea level static SLS-ISA conditions for an uninstalled engine, the FDR reported values for the fuel flow rates which reflect the at altitude conditions for an installed engine. The fuel flow rates are first converted to equivalent values referenced to SLS-ISA conditions for an uninstalled engine. This process allows a comparison of the ICAO databank and the FDR derived values. Lastly, these FDR derived mean values are statistically compared with the corresponding values in the ICAO databank. The mean operational values in the different phases of the LTO cycle were found to behave qualitatively similar to those in the ICAO databank[48]. However, in almost all of the cases, the actual mean operational values differed in a statistically significant manner from those reported in the ICAO databank, and the latter were found to typically be greater than the former. The differences found between the ICAO databank and operational values can lead to an inaccurate estimation of fuel burn and global aircraft emission inventories, which currently rely on the ICAO databank to estimate emissions[48]. Even though this method is more accurate in calculating emission, accessibility to large volumes of airport wide FDR data is extremely limited due to various administrative barriers maintained by airlines.

Travis M. Norton(2014) found new methodology to improve the accuracy of emission calculation in aviation industry[49]. In this approach, the airport specific information was gathered from FAA Operations and Performance Data Traffic Flow Management Counts (TFMSC). This database provides traffic counts by the airport for different data groupings used by airport location, aircraft type and by year. The traffic count data was input into the FAA's EDMS modelling software which uses engine specifications to calculate emissions for each aircraft type. EDMS produces fuel consumption, water vapour, and CO_2 inventories for the LTO phase[49]. The EDMS has been replaced by the AEDT as of May 2015[50]. AEDT is currently used by the U.S. government and AEDT requires administrative privileges for both installation and execution of the software[50].

The main limitation that operational values are deviating from ICAO values is reduced engine thrust during take-off. This practice is often carried out for performance and cost-efficiency reasons[51]. It may depend on aircraft weight and weather factors [52] and this could lead to an overestimation of emissions from airports. It has been reported that most aircraft use a thrust of 3%- 4% Foo instead of 7%Foo for taxiing[52]. Moreover, higher thrust levels are sometimes used for turning along the taxiways with acceleration and deceleration of the engines due to congestion which is responsible for significant increases in fuel consumption and emissions[53]. For example, Khadilkar and Balakrishnan (2011)[54] observed that total fuel burn during departures and arrivals at airports is generally overestimated by the ICAO method with respect to emissions computed from real-time aircraft flight data.

2.2 Tools used to gather information on flight operations and emission factors

2.2.1 Automatic dependent surveillance-broadcast (ADS-B)

The aircraft is able to determine its position via satellite navigation and enables to be tracked with the use of ADS-b. The information is received by air traffic control ground stations as a replacement for the secondary surveillance radar, which is used by air traffic controllers to determine distance, altitude, aircraft ID, and velocity through an onboard transmitter. The information can also be received by other aircraft to provide situational awareness. ADS–B equipment is mandatory for IFR category aircraft in Australian airspace and for some aircraft in Europe since 2017. ADS-B improves aviation safety by making an aircraft visible, real-time, to ATC and other aircraft that are equipped with ADS-B with position and velocity data transmitted every second. This system provides more accurate information than the current radar-based systems. This system reduces the amount of time aircraft must spend waiting for clearance and holding since ATC is well informed with accurate position of flights. Therefore, ADS-b has benefits by reducing pollution and fuel consumption[55].

ADS-b operates in the entire Sri Lankan airspace[56] and Real-time data of flights are received. Since a huge volume of data is received via this technology at once, data storage can be very expensive. Hence most local stakeholder organizations tend to discard data after a short period of time. Thus, an enormous amount of data need to be stored and processed in order to be used as input for carbon emission estimation. This is one of the challenges for using raw ADS-B data for developing GHG inventories. However, there are other third-party organizations such as Flightradar24 and FlightAware that provide access to processed ADS-B data on flight by flight basis.

2.2.2 Flightradar24

Flightradar24 is a global flight tracker that provides real-time information about aircraft around the world. The service is available online and shows live air traffic from around the world. Flightradar24 receives data from several sources and ADS-B, MLAT, radar data are the main sources. Those data sources are aggregated together with flight status data from airlines and airports to create a unique flight tracking experience on www.flightradar24.com and in Flightradar24 apps. Most major airports normally have coverage Flightradar24 [57] including BIA. Flightradar24 records timings of different phases of flight in minutes. As the national flag carrier and as the main ground handler at BIA, Sri Lankan airline uses Flightradar24 to track the flights in order to take necessary actions.

2.2.3 FlightAware

FlightAware is the largest flight tracking digital aviation company in the globe and it is founded in 2005. FlightAware provides global flight tracking solutions, predictive technology, analytics, and decision-making tools over 10,000 aircraft operators and service providers. This technology receives data from various sources. Air traffic control systems in over 45 countries, ADS-B ground stations in 195 countries, Aireon global space-based global ADS-B, and datalink (satellite/VHF) are those data sources of FlightAware which made it the largest flight tracker. FlightAware is responsive and reliable web-based interface and it maintains comprehensive and capable flight tracking and digital aviation data platform.

FlightAware records timings of different phases of flight in seconds. Since the fuel flow rate of different phases of flight according to the engine type was given in ‘kg per second’ by ICAO Aircraft Engine Emissions Databank[58], actual fuel flow under different phases can be accurately calculated using FlightAware.

2.2.4 Airport Carbon and Emissions Reporting Tool (ACERT)

The ACERT is a simple IT solution and Excel spreadsheet that calculates GHG emissions at the airport and it generates an informative airport GHG emissions inventory report. This report contains the assumptions and caveats and a check-list to aid review. This tool is available at no cost to airports and it does not require emissions or environmental expertise whereas only operational data is required. ACERT provides an opportunity to evaluate the emission footprint and environmental performance at the airport. The methodologies used in calculations are consistent with the ACI Guidance Manual on Airport Greenhouse Gas Emissions Management (2009) and the GHG Protocol [59].

Since the ACERT tool helps to calculate the emission from all the sources within the airport vicinity, emission from the taxiing phase and emission from the APU can be calculated using this tool. However, aircraft type, taxiing duration and duration of APU usage should be provided to ACERT.

2.2.5 Emission index (EI)

An emission index is defined as the mass of pollutant emitted per unit mass of fuel burned for a specified engine. The ICAO Engine Emissions Data Bank (EEDB) provides the EI for certified engines in units of grams of pollutant per kilogram of fuel (g/kg) for NO_x, CO and HC, as well as the mode-specific fuel flow in units of kilograms per second (kg/s), for the four power settings of the engine emissions certification scheme. The ICAO Aircraft Engine Emissions Databank is maintained by the European Aviation Safety Agency (EASA) on behalf of the ICAO and contains information on exhaust emissions for aircraft engines that have entered production Multiplying the mode-specific EI by the TIM-specific fuel flow more accurate inventories can be calculated[51].

EI for CO_2 ($EICO_2$= 3.16 kg/kg fuel) is mode independent and only a function of aviation fuel burnt [60][61]. Therefore, the fuel consumption of aircraft under different phases is required when calculating CO_2 emission.

2.2.6 Carbon emission accreditation

The Airport Carbon Accreditation which is a certification programme launched by the ACI developed to assess the efforts of airport operators in reducing GHG emission. Then the airport operators have to follow step by step process in order to become Airport Carbon Accredited. Mapping, reduction, optimization and neutrality are the four steps to follow by airport operators. The mapping step calculates the current carbon footprint and prepares the corresponding report. The reduction step requires the fulfilment of the mapping step and demonstrates the effectiveness of emission reduction actions to reduce emissions. The optimization step involves commitments with third parties that operate within the airport. The neutrality step is achieved by neutralizing the remaining amount of direct emissions, through compensating actions. Only CO_2 emission management is mandatory for this scheme[62].

However, this method does not address the emission from different phases of flight separately since it gives the priority to emission sources at the airport vicinity. In most regions, airport operators are not yet required by government regulation to take action on GHG emissions. Therefore, few airports voluntarily involve reducing emissions.

2.3 Auxiliary power units (APUs)

APUs are used when no other power source is available for the aircraft and may vary from airport to airport. The use of APUs is severely restricted at some airports to maintain high levels of air quality, and therefore this source of fuel use and emissions may be declining. The international aviation emissions cover all phases of flight and APU fuel burn. Even though APU emissions could be considered a ground activity, in practice, airport operators cannot easily determine the APU emissions.

2.3.1 APU usage at different airports

In Zurich Airport, APU shall only be started to start the main engine of the aircraft, but earliest 5 minutes before off-block time. If maintenance work on the aircraft makes it unavoidable; in that case, the service period shall be kept as short as possible while operating APU. If the stationary or mobile units are not available or unserviceable for specific aircraft types then the APU can be operated. In that case, the APU shall be started at the earliest 60 minutes before off-block time and kept in operation not more than 20 minutes after the on-block time[63]. Some airlines establish a company based APU usage procedures that can be dependent on the type of aircraft, take-off weight and characterization of the airport, for illustration, altitude, runway length and such like.

Some airports have followed the mandatory process of switching off the APU when aircraft are parked at the gate. Barcelona El Prat Airport uses fixed ground power and pre-conditioned air from two minutes after the aircraft arrives at a terminal gate until five minutes before it leaves which is mandatory[64]. In December 2014, Hong Kong Airport banned the use of auxiliary power units by aircraft and consequently, the airport invested over $7.8 million to upgrade all its fixed ground power and pre-conditioned air systems[64].

2.4 Taxiing delays and calculation methods

Current industry practice for calculating taxiing delay is based on a reference value which was statistically computed using historical data of the airport. The additional taxiing time is defined by ICAO as the difference between the actual taxiing time and a reference taxiing time (unimpeded)[65]. ICAO proposes two approaches for calculating the unimpeded time. The basic method recommends using the 20th percentile of actual taxiing time. The advanced method recommends to separate value for each gate and runway combination and to use the average actual taxiing time during non-congested periods [66]. Both approaches are accepted and used in European industry [67]. Currently, the industry defines the reference value for the unimpeded taxiing time as the 20th percentile of observations [68][69]. European Union and FAA follow for the application of a consistent methodology for determining unimpeded taxiing time. The method uses the 20th percentile of the distribution of observed values [68].

3. METHODOLOGY

3.1 Research Problem

3.1.1 Evaluation of CO_2 emission level within the LTO cycle

NDCs under aviation considers only the emission from domestic flights and the emission from airport operations as the national emission of aviation sector in a country. Emissions from international flights within the LTO cycle and emission from its APUs are not considered by the NDCs even those significantly influence to the local air quality. Emission from the international flights within the LTO cycle and the emission from its APUs should also be addressed by the countries to reduce their emission contribution to the atmosphere.

Although the emission is an overriding concern of the aviation sector, identification and evaluation of airport related emission has received limited attention. Influence of aviation specifically on ground air quality is mainly from emission aroused due to airport operation (aircraft and other sources). Among other sources, emission from aircraft operation (APU and LTO) is one of the major contributors to overall emission from airports. As demand for air travel grows, the rate of increase in aircraft emission grows in parallel surpassing the same in other sources.

Based on the extensive literature review, the research gap identified is the lack of research attention for developing alternative methods for evaluating GHG emission due to aircraft activity (APU and LTO) at airports. Limitations of current methods are as follows:
Highly data intensive methods: These methods require aircraft activity data including fuel consumption in each LTO phase, time spent in each phase for all the flights operated with in the time period of interest. Sources used to obtain such data are flight data recorder, electronic flight processing strips (EFPS) or proprietary software such as Aviation Environmental Design Tool (AEDT) used by FAA. Most small to medium size airports particularly in developing countries do not have access to such detail data on aircraft activity.

Less data intensive methods such as ICAO option B rely on broad industry wide parameters such as Time in Mode (TIM) (time spent by an aircraft in each LTO phase) having significant deviations with respect to individual airport conditions. These deviations most often cause over estimation of GHG emission compare to actual levels. Furthermore, this method estimates GHG emission aggregated over taxing-in and out phases, hence provide limited capability to identify opportunity for improvements.

3.2 Research Framework

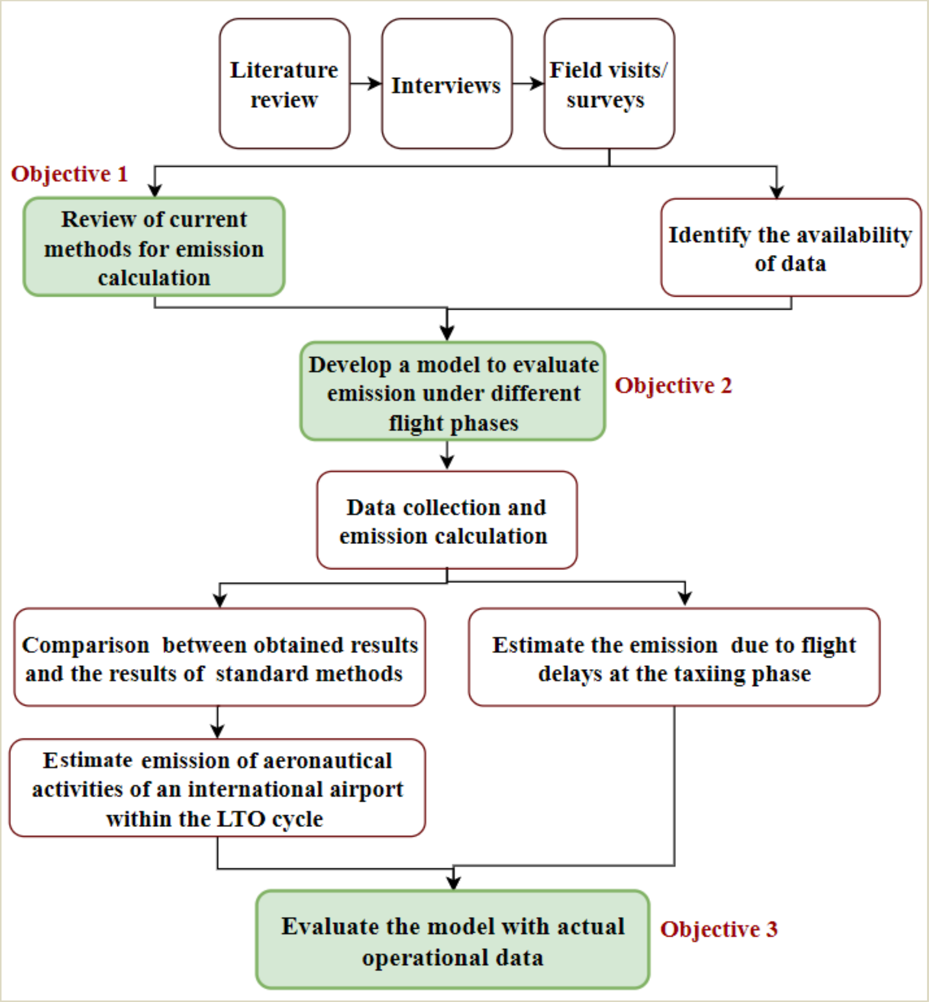


Figure 3.1: Research Framework

The relevant research papers, annexes, manuals, annual reports were referred to as secondary data to identify the previously conducted methodologies for emission calculation in international civil aviation. Different methodologies suggested by various international bodies and its applicability to the selected airport were identified. Aiming to identify the operation of the selected airport due to limited records under the emission calculations, interviews and field visits were conducted. The availability of data that are required to follow different methodologies of emission calculation was identified through interviews and field visits. An overview of current emission calculation methods in the industry was developed by studying the methodologies and the data used for calculations. Conducting the interviews with relevant parties, the data availability was searched.

Actual time durations under different flight phases for every flight during the period under study (typically one year) is required to calculate CO_2 emissions. Unfortunately, many airports may not have access to such a detailed data set accumulated over a long period. Hence a less data-intensive method is required. This methodology aligns with the ICAO simple approach option B method. As pointed out in the previous section, the ICAO option B method recognizes the different phases of the LTO cycle. A major limitation in this method is that it estimates fuel burn based on a set of standard values for the time spent in each mode or phase within the TLO cycle. The proposed method in this study uses available operational data to estimate the average time spent in each phase instead of using standard values.

3.2.1 Proposed model to estimate the CO_2 emission level within the LTO cycle

The Tier 1 and 2 methods suggested by IPCC in calculating emission cannot be applied to this study directly as they lack the ability to recognize the site-specific conditions and do not support to calculate CO_2 emission under different phases separately. Tier 3 method needs more advanced tools and software which are not available at the moment at the selected airport. Data intensive methods such as using Electronic flight data strips and Flight data recorder have limited application in most small to medium size airports in developing countries due to lack of data sources.

In order to achieve the objectives mentioned at the beginning of the current chapter, a modified ICAO option B method is proposed in the study to estimate the CO_2 emission levels due to aircraft operations at an airport. Advantage of the ICAO the simple approach option B method is that it’s mathematically simple model structure and less data intensive. Major limitations of the methodology are:

- It uses ICAO standard TIM values in order to estimate the fuel consumption of each operation and the limitation with the standard TIM values fails to recognize conditions specific to the airport thus over/underestimating the CO_2 emission levels.

- The method cannot take into account CO_2 emission due to APU usage.
- Aggregated CO_2 estimation. This limits the application of the methodology to assess critical phases within the LTO cycle causing excessive CO_2 emission levels.

Recognizing the airport specific conditions in CO_2 emission level estimation

Most airports cannot directly apply existing methods in CO_2 emission calculation. Some emission calculation methods are highly data-intensive methods that use EFPS, AEDT and FDR data and utilize software tools which are inaccessible to most airports. Other methods while less data-intensive, however, they use broad industry-wide parameters (TIM) which has significant deviations concerning individual airport conditions. The methodology proposed in this study fills the gap in between the above two extremes. It uses available operational data that is available with most airports particularly ones with fewer resources. It is less data-intensive as it requires a representative sample of operational data to estimate the new TIM values. It is more accurate when estimating CO_2 emission compared to using industry-wide standard TIM values. Furthermore, the methodology allows disaggregating the emission within the LTO cycle, which enables taking corrective action towards reducing excessive emission. The suggested methodology of this research can be applied to any other airport with similar conditions to the case studied. Figure 3.2 indicates a template developed for other airports to follow to improve their estimates of CO_2 emission with minimal resources.

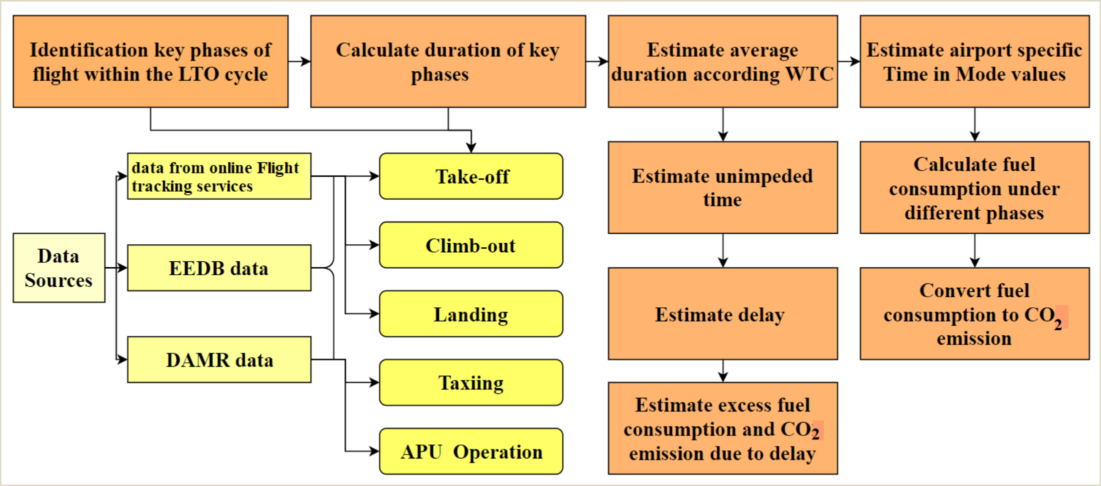


Figure 3.2: A template for other airports for estimating its emission with minimal resources

3.2.2 Methodology for the analysis of excess CO_2 emission due to delays

The excess emission is assumed to be generated primarily by two sources, such as inefficient procedures in handling aircrafts within the LTO cycle (long taxing routs, active runway crossings, air traffic controlling methods, etc.) and delay due to capacity constraints in the air traffic flow management. The two sources can be interrelated where, streamlining certain aircraft handling procedures could increase existing airside capacity. Therefore, evaluating excess emission and its sources is essential in order to determine most effective strategies of emission reduction.

Often delays are experienced in taxing phases and approach phase of the LTO cycle. However, delays at the approach phase at BIA can be assumed as negligible due to low operations at the selected airport. Due to proper sequencing and separations maintained for the departure flights, delays in the take-off and climb-out phases can be assumed negligible. Delay for a given flight operation *i* in LTO phase *j* is given by:

$$\mathrm{Delay} = \mathrm{AT_{ij}} - \mathrm{UT_{ij}} \tag{08}$$

Where; $\mathrm{AT_{ij}}$: Actual operating time of the $\mathrm{i^{th}}$ operation in the $\mathrm{j^{th}}$ phase (minutes)

$\mathrm{UT_{ij}}$ **:** Unimpeded operating time for the $\mathrm{j^{th}}$ phase (minutes)

Therefore, considering the available technology and the data, a methodology was developed to calculate CO_2 emission due to at the taxiing phase only.

3.3 Phases of flight within the LTO cycle

This study took into consideration the following phases of the LTO cycle separated according to arrivals and departures.

3.3.1 Departure flight

- Aircraft at the gate - When the passengers embark on the aircraft, energy is needed to the aircraft for air-conditioning, lighting and the power to start the main engine. It is provided by the APU of the aircraft or GPU (Ground Power Unit). Then the aircraft waits at the gate until the pushback clearance issued by the ground controllers once the taxiways are clear.
- Pushback - When the aircraft receives the clearance according to the congestion level of taxiways, it is pushed backwards away from the gate towards the taxi-lane. APU operates at this phase. The engines are usually started during the push-back period.
- Taxi-out – the movement of an aircraft when it travels on the ground, between the beginning of the taxiway and the take-off threshold point of the runway. The main engine operates at this stage. The ground controller is responsible for issuing taxi clearances by observing congestion level at the taxiways. The ground controllers share information of "movement area" with the tower controller**.** The ground controller is in charge of the taxiways while the tower controller is in charge of the runways.
- Take-off roll- the movement of an aircraft when it travels along the runway before it leaves the ground. The take-off roll starts when the aircraft enters the runway from the taxiway. Take-off clearance from ATC is required to enter the runway.
- Take-off is the phase of flight which an aircraft leaves the ground. An aircraft requires a lot of power to take off, and therefore, the maximum thrust at the power setting will be set for take-off.

- Initial Climb- That portion of flight operation between takeoff and the 3000feet altitude. The wheels are drawn back as soon as the aircraft is airborne in order to lift the aircraft[8].

3.3.2 Arrival flight

- Approach – the movement of the aircraft between 3,000 feet altitude and touch down point at the runway. The aircraft will gradually slow down, and the wheels will be lowered. At this stage, the landing clearance is required from the tower controller[8].
- Landing – The movement of arrival flight between touch down and leaving point at the runway.
- Taxi-in - the movement of an arrival flight on the ground between the point where it leaves the runway and enters to a designated arrival bay. Once aircraft arrives in the parking bay and it shuts down engines. While taxiing towards the gate, the aircraft switch on its APU.
- Aircraft at parking bay - When the passengers and crew members disembark the aircraft, air-conditioning and lighting are provided by the APU of the aircraft or GPU.
- Aircraft turnaround - the time required to unload an aircraft after its arrival at the gate and to prepare it for departure again. APU or GPU operates within this period and the duration of APU/GPU operation is decided by the particular airline. Different airlines follow different policies in APU/GPU operation.

GHG emission from aviation arises from the combustion of jet fuel and aviation gasoline. Emission arises during all activities related to flight movements since fuel is burnt. Aircraft engine and the APU consume the aviation fuel and emit GHGs to the atmosphere. The main phases of both arrival and departure flight within the LTO cycle (below 3000 feet) are indicated above. The departure flight includes the phases such as taxi-out, take-off and initial climb where aircraft main engine operates. The arrival flight includes the phases such as approach, landing and taxi-in where the main engine operates. The activities that take place during the departure and arrival phases where the main engine operates are reported together as ‘landing and take-off’ (LTO) activities in the aviation inventory domain. The turnaround phase where APU operates is excluded from the LTO cycle.

3.3.3 Auxiliary Power Unit (APU)

Most aircraft use an APU to generate power when the aircraft is on the ground. It is a small engine that is used when the main engine is turned off at the ground. APU operates when passengers are embarking and disembarking from the aircraft in order to provide air conditioning and lighting. APU power is needed to switch on the main engine. The cleaners can plug their equipment once the APU provides power. APU also consumes jet fuel in the same manner as the main engine does.

Few airports use Ground Power Units (GPUs) to support APU while reducing APU usage at the airport. Ground power units consume cheaper energy sources compared to aviation fuel. Since the APU is needed to switch on the main engine, APU can be switched on just before the aircraft is due to depart. Nice Côte d'Azur Airport installed a GPU system in 2014, and the system has cut annual CO_2 emissions by 416 tons [70].

3.4 Carbon Dioxide (CO_2) Emission

The CAEP of ICAO, during their 7th Meeting in Montreal in 2007, it was declared that the CO_2 emission from aircraft that affects climate change is clearly identifiable and quantifiable while the other substances, such as methane or nitrogen oxides, are not yet fully quantified [71].

Most greenhouse gas inventories are measured with CO_2 emissions. However, there are different greenhouse gasses beyond CO_2. The most significant GHG associated with airport operations is also CO_2 and therefore, CO_2 is mainly focused in GHG inventories. However, when an inventory includes other GHGs, they are reported as “carbon dioxide equivalent” (CO_2-eq) by multiplying the emission value with a weight (Global warming potential) [72]. Generally, CO_2 represents over 95 per cent of the emissions at most airports [73].

3.5 Data Sources

This study made a thorough exploration of available data sources to estimate the relevant parameters of the methodology. For the particular case of Bandaranaike International airport, there was no single source of data covering all the phases of the LTO cycle. In most such airports limited operational data is collected as stored for a limited period mainly for accident investigation purposes. This study was able to identify two sources of available data to estimate the parameters of TIM values. Two sources separately cover the airborne phases (Take-off, climb-out and approach) and aircraft-on-ground phases (pushback, taxing-out and taxing-in).

3.5.1 Taxiing phase and Turnaround

Durations under different phases of flight according to aircraft type is critical factor for emission calculation. Few methods were suggested in literature to calculate accurate durations. Even though these durations were recorded, those data are restricted to access. Primary data were obtained by interviews with industry experts and the Daily Aircraft Movement Record (DAMR) data from ATC. DAMR data was used for calculating durations of the taxiing phase and the turnaround. The DAMR database contains information such as aircraft type, movement type (arrival, departure, touch & go), take-off time/ landing time (wheels off/ wheels on), the category of flight (scheduled, non- scheduled), gate departure/ gate arrival time and parking bay. ATC maintains this record for each scheduled and non-scheduled flight that use the runway. It tracks the aircraft and records the time of the flight at specific places at the airport. These data were used to estimate average aircraft turnaround time and taxiing time. The aircraft turnaround time was needed to determine the APU usage and its emission.

ACERT of ACI was used to obtain emission factors at the taxiing phases and APU usage according to the aircraft engine type in order to calculate emissions.

3.5.2 Take-off, Climb-out and Approach

Climb-out phase as described above includes the duration of flight from take-off (wheels off) to reaching an altitude of 3000ft and approach includes the time duration from 3000ft down to landing (wheels on). Air navigation service providers keep a full record of all flight operations in the relevant airspace mainly as a mandatory requirement for accident investigations. However, such data cannot be feasibly filtered and processed to extract the above specific portion of flight within the LTO cycle.

Data obtained from the Automated Dependent Surveillance- Broadcast (ADS-B) can be used as an alternative source of data in order to estimate the average time durations of climb out and approach phases of different flight categories. There are several online platforms that collect, process and visualize ADS-B data for commercial purpose. In order to estimate the average time taken within the airborne phases of the LTO cycle, this study collected data by observing a sample of flight operations using data provided by an online flight tracking service. These online flight tracking platforms provide a recorded history of flights between a given origin and destination airports. The data provided includes variation of key flight parameters (flight altitude (calibrated), speed (relative to ground and air) and flight path) with respect to time. These online flight tracking services primarily make use of data obtained from ADS-B sources. Online flight tracking services such as FlightAware.com and Flightradar24.com were referred in this study in order to extract durations of take-off, climb and approach for a representative sample of flights operating to and from the selected airport. Online surveys were conducted to track the flights used the selected runway with the use of FlightAware. The Flightradar24 used track the same flights in to increase the accuracy level. This website is an internet based service provider that provides real-time information on commercial flights. The time durations spent on take-off, climb-out and approach phases were calculated using the data received from FlightAware.

The fuel flow rates under the phases of take-off, climb-out and approach according to the aircraft types, were obtained from the by ICAO Aircraft Engine Emissions Databank[58] for the CO_2 emission calculation.

3.5.3 ICAO Aircraft Engine Emissions Databank

The ICAO Aircraft Engine Emissions Databank was used to obtain fuel flow rates according to the aircraft type under different phases of flight. The databank contains information on exhaust emissions of aircraft engines and the calculation process is done according to the procedures in ICAO Annex 16, Volume II. The EASA hosts the databank on behalf of ICAO and is not responsible for the information which is provided by engine manufacturers who are responsible for the accuracy of data. Engine manufacturers submit information on aircraft engine to the primary certification authority (CA) for approval. Once the approval is obtained by the primary CA, manufacturers can voluntarily submit it to EASA what checks the data before publishing in engine emission databank [58].

3.5.4 Emission index (EI)

An emission index is defined as the mass of pollutant emitted per unit mass of fuel burned for a specified engine. The ICAO Engine Exhaust Emissions Data Bank (EEDB) provides the EI for certified engines in units of grams of pollutant per kilogram of fuel (g/kg) for NO_x, CO and HC, as well as the mode-specific fuel flow in units of kilogram per second (kg/s), for the four power settings of the engine emissions certification scheme [39].

EI for CO_2 ($EICO_2$= 3.16 kg/kg fuel) is mode independent and only a function of aviation fuel burnt [60][61]. Therefore, the fuel consumption of aircraft under different phases is required when calculating CO_2 emission.

3.6 Data Collection

Actual time durations under different flight phases are required to calculate CO_2 emissions. Available literature recommends various methods to calculate accurate durations.

However, with the available technologies at the selected airport, DAMR data was selected to obtain data to calculate CO_2 emission at the taxiing and turnaround phases. Since the ATC maintains DAMR daily and stores in a database, it is contained data of past flights. FlightAware is used to obtain the data that is required to calculate emission of take-off, climb-out and approach phases.

CO_2 emission within the LTO cycle was considered for this study and different phases of flight within the LTO cycle are separately evaluated. Each phase of flight has specific fuel flow rate according to the engine type and aircraft spends different durations under different phases. For an illustration, according to the ICAO, average duration of take- off is 0.7 minutes while average duration for climb-out is 2.2 minutes, the approach takes 4 minutes and taxiing takes 26 minutes[45].

According to the availability of data, some phases were merged and the durations of merged phases were obtained for the emission calculation. For an example, DAMR provides the timing of gate departure and take-off of departure flights and timing of touch down and gate arrival of arrival flight. Therefore, for the departure flight, the duration of pushback, take-off roll cannot be identified separately with the available data and those durations were considered as a part of taxiing-out phase. In arrival flight, duration of landing roll cannot be identified separately with the available data at DAMR. Therefore, duration of landing roll was considered as a part of taxiing in phase. When obtaining data for calculating durations using the FlightAware, the take-off and climb-out phases were merged and calculated the aggregate duration of those two phases. Since the take-off phase takes few seconds, it is difficult to identify exact duration spent for taking-off using FlightAware.

3.7 Estimating emission under different phases of flight

3.7.1 Aircraft Categorization

Aircraft are categorized under different characteristics. The ICAO wake turbulence category (WTC) is based on the maximum certificated take-off mass of aircraft. Heavy, Medium and Light are the aircraft categories under WTC. Heavy aircraft are with a weight of 136 000 kg or more and Medium aircraft are less than 136 000 kg and more than 7 000 kg whereas Light aircraft are with a weight of 7000kg or less[74].

3.7.2 Taxiing phase

According to the availability of data at the selected airport, some phases were merged and the durations of merged phases were obtained for the emission calculation. DAMR provides the timing of gate departure and take-off, therefore the duration of pushback and take-off roll cannot be identified separately with the available data and those phases were considered as a part of the taxiing-out phase. Take-off is usually a small portion of the flight mission and it can be assumed that for the first few seconds of the flight. The ICAO suggests that average take-off time is about 0.7 minutes. DAMR provides the timing of touch down and gate arrival therefore, duration of landing roll cannot be identified separately, and landing roll phase was considered as a part of the taxiing-in phase.

Taxiing times were categorized as taxiing in time for arrivals and taxiing out time for departures. They were analyzed separately. The taxiing in time of each arrival was calculated using Equation 09 and taxiing-out time of each departure was calculated using Equation 10. The data of 3 months were used for the initial analysis. DAMR records the time of specific places where the aircraft reports.

$$\mathrm{T_{TI}} = \mathrm{T_{GA}} - \mathrm{T_{TD}} \tag{09}$$

$$\mathrm{T_{TO}} = \mathrm{T_{TOFF}} - \mathrm{T_{GD}} \tag{10}$$

Where; $\mathrm{T_{TI}}$: Taxiing-in time,

$\mathrm{T_{TO}}$: Taxiing-out time,

$\mathrm{T_{GA}}$: Gate arrival time,

$\mathrm{T_{TD}}$: Touchdown time,

$\mathrm{T_{TOFF}}$: Take-off time,

$\mathrm{T_{GD}}$: Gate departure time.

Typically, taxiing time depends on various factors such as runway capacity, runway, taxiway and apron configuration, wind direction, weather and inefficiencies on ATC. The factors that influence to taxiing at the selected airport were needed to be recognized. According to the available data, taxiing time was categorized into different categories in order to identify the factors affecting the taxiing time. Taxiing time according to the parking apron (A, B, C and D), the day of the week (Monday to Sunday) and ICAO Wake Turbulence Category (WTC) (heavy, medium and light) were the subcategories used for this analysis. It was checked whether the taxiing time was influenced by the parking apron, the day of the week and WTC.

ANOVA test on the taxiing time

The ANOVA test was conducted under different subcategories to identify all the sample means within the group are equal or the factor did not have any significant effect on the results. The null hypothesis for the ANOVA test was that all the sample means are equal or the factor (apron/day/WTC) did not have any significant effect on the results (taxiing time). Whereas, the alternate hypothesis is that at least one of the sample means is different from another and that indicates the specific factor (apron/day/WTC) has a significant influence on taxiing time. When results rejected the null hypothesis, the t-test was conducted to check which samples had different means.

However, Taxiing time distribution of WTC was selected for further analysis after the ANOVA test.

Comparison of average taxiing time with ICAO recommended values

Once the taxiing in and out times were categorized according to the WTC, average taxiing time under each category was calculated. Three different taxi-in means and three different taxi-out means were obtained for the selected airport according to the WTC. The average Taxi in for arrivals 7 minutes and average taxi-out time for departures 19 minutes are the ICAO suggested timings without considering the WTC of aircraft. By assuming the ICAO values are the mean of the population, one sample t-test was conducted to check the calculated taxiing mean of the selected runway and ICAO mean are significantly different from each other. The 3 average taxiing in times according to the WCT were compared with ICAO suggested average taxiing in time of 7 minutes. The 3 average taxiing out times according to the WTC were compared with ICAO suggested average taxiing out time of 19 minutes. This comparison was conducted to identify whether the ICAO suggested values can be directly applied to the selected runway when calculating CO_2 emission.

Converting taxiing time to CO_2 emission

When calculating CO_2 emission, the IPCC suggested basic method was followed in each phase of flight within the LTO cycle. The fuel burn rate and Emission Factors under each phase of flight according to the aircraft type was used for this calculation. It is assumed that fuel burn rate is consistent throughout the taxiing phase.

Converting taxiing time to CO_2 emission with raw data

Then the taxiing time of both arrival and departure was converted to fuel consumption using Equation 11 and 12. The taxiing time of both arrival and departures was converted to CO_2 emission using Equation 13 and 14. The fuel burn rate and the emission factors under different aircraft types were obtained from the ACI recommended ACERT tool.

$$\mathrm{FC} = \mathrm{T_{TI}} \times \mathrm{FBR} \tag{11}$$

$$\mathrm{FC} = \mathrm{T_{TO}} \times \mathrm{FBR} \tag{12}$$

$$\mathrm{CO_2\ Emission_{taxiing\ in}} = \mathrm{T_{TI}} \times \mathrm{EF} \tag{13}$$

$$\mathrm{CO_2\ Emission_{taxiing\ out}} = \mathrm{T_{TO}} \times \mathrm{EF} \tag{14}$$

Where; FC: Fuel consumption (kg),

T_{TI}: Taxiing-in time (minutes),

T_{TO}: Taxiing-out time (minutes),

FBR: Fuel burn rate according to aircraft type (kg per minute)

EF: Emission factor according to aircraft type (kg per minute).

Converting taxiing time to CO_2 emission using the suggested methodology

The average taxiing time of both arrival and departure in the selected runway was converted to fuel consumption using Equation 15 and 16. Then the average taxiing time of both arrival and departures was converted to CO_2 emission using equation 17 and 18. The average fuel burn rate and the emission factors according to WTC was calculated.

$$\mathrm{FC} = \mathrm{AT}_{\mathrm{TI}} \times \mathrm{FBR} \tag{15}$$

$$\mathrm{FC} = \mathrm{AT}_{\mathrm{TO}} \times \mathrm{FBR} \tag{16}$$

$$\mathrm{CO_2\ Emission}_{\mathrm{taxiing\ in}} = \mathrm{T}_{\mathrm{TI}} \times \mathrm{EF} \tag{17}$$

$$\mathrm{CO_2\ Emission}_{\mathrm{taxiing\ out}} = \mathrm{T}_{\mathrm{TO}} \times \mathrm{EF} \tag{18}$$

Where; FC: Fuel consumption (kg),

AT_{TI}: Average Taxiing-in time at the selected airport (minutes),

AT_{TO}: Average Taxiing-out time at the selected airport (minutes),

FBR: Average Fuel burn rate according to WTC (kg per minute)

EF: Average Emission factor according to WTC (kg per minute).

Comparison of the taxiing emission obtained from the operational data, suggested methodology, and ICAO option B method

The CO_2 emission from the taxiing phase was calculated using actual raw data, the suggested methodology and the ICAO option B method and 3 results were compared with each other.

3.7.3 Take-off, Climb-out and Approach phases

The time consumed at the take-off and climb-out of phases of departures and the time consumed for the approach phase of arrivals were the required data. An online survey was conducted to track those data of flights operating at the selected airport within a week. FlightAware website was used to track the data.

Take-off is usually a small portion of the flight mission and it can be assumed that for the first few minutes of the flight. The ICAO suggests that average take-off time is just 0.7 minutes and take-off process is governed by aircraft performance and is influenced little by conditions at the originating airport. Therefore, it is assumed that take-off time is not likely to be affected by delays or other inefficiencies in the system. None of the available data sources were able to differentiate the time taken for this phase. Thus, actual take-off time can be assumed to be equal to take-off time under the baseline scenario[60].

Time taken for Climb-out and approach phases was estimated using the data collected by observing the recorded history of a sample of departing and arriving flights respectively. Climb-out time for each flight was obtained by taking the time gap between last time point of 0 feet altitude (assumed as the time point of main gear lift off) and the time point of 3000 feet altitude. Similarly, the approach phase time for each arriving flight was obtained by taking the time gap between the time point of 3000 feet altitude and the first time point of 0 feet altitude (assumed as the time point of main gear touch down).

$$\text{Climb out time} = \text{time}_{3000\text{ft}} - \text{time}_{\text{lift-off}} \tag{19a}$$
$$\text{Approach time} = \text{time}_{\text{touch down}} - \text{time}_{3000\text{ft}} \tag{19b}$$

Comparison of the mean durations of climb-out and approach phases with ICAO recommended values

The average climb-out according to aircraft types were compared with ICAO recommended standards. The ICAO recommended value for the average climb out time is 2.2 minutes. The one sample t-test was conducted to check whether the calculated means under the climb-out phase according to the aircraft types of the selected airport and the ICAO mean value are significantly different from each other.

Duration of the approach can be calculated using the data obtained from the FlightAware. The average approach times according to heavy and medium aircraft were compared with the ICAO recommended mean value of 4 minutes. The one sample t-test was conducted to check whether the calculated means under the approach phase according to the heavy and medium flights of the selected airport and the ICAO mean value are significantly different from each other.

Converting durations in take-off, approach and climb-out to CO_2 emission

Converting durations in take-off, approach and climb-out to CO_2 emission using raw data

The time spent at take-off, climb-out and approach phases were converted to fuel consumption and CO_2 emission by using fuel burn rate and EF according to the aircraft type. The fuel burn rates were obtained from the ICAO engine exhaust emissions data bank. Equation 20, 21 and 22 indicate the fuel consumption of take-off, climb-out and approach phases. Emission Index (EI) for CO_2 ($EICO_2$= 3.16 kg/kg fuel) is mode independent and only a function of aviation fuel burnt [60][61]. This EI was used for the aircraft when it is in the air. Equation 23, 24 and 25 indicate the CO_2 emission generated at the phases of take-off, climb-out and approach.

$$FC_{take-off} = FBR_{take-off} \times D_{TOFF,ICAO\ value} \times \mathrm{N_j} \tag{20}$$

$$FC_{climb-out} = FBR_{climb-out} \times D_{CO} \times \mathrm{N_j} \tag{21}$$

$$FC_{approach} = FBR_{approach} \times D_{A} \times \mathrm{N_j} \tag{22}$$

$$CO_2Emission_{take-off} = D_{TOFF,ICAO\ value} \times EI \times \mathrm{N_j} \tag{23}$$

$$CO_2Emission_{climb-out} = D_{CO} \times EI \times \mathrm{N_j} \tag{24}$$

$$CO_2Emission_{approach} = D_{A} \times EI \times \mathrm{N_j} \tag{25}$$

Where; FBR: Fuel Burn Rate according to aircraft type (kg per second),

D_{CO}: Duration of Climb-out (seconds),

D_{TOFF}: Duration of take-off (seconds),

D_A: Duration of approach (seconds),

FC: Fuel consumption (kg),

EI: Emission Index (kg per second)

N_j: number of engines used on aircraft type j.

Converting durations in take-off, approach and climb-out to CO_2 emission using suggested methodology

The average time spent at take-off, climb-out and approach phases at the selected airport were converted to fuel consumption and CO_2 emission by using average fuel burn rate and Emission Factors according to the WTC. Equation 26, 27 and 28 indicate the fuel consumption of take-off, climb-out and approach phases. Equation 29, 30 and 31 indicate the CO_2 emission generated at the phases of take-off, climb-out and approach according to the suggested methodology.

$$FC_{take-off} = AFBR_{take-off} \times AD_{TOFF} \times \mathrm{N_j} \tag{26}$$

$$FC_{climb-out} = AFBR_{climb-out} \times AD_{CO} \times \mathrm{N_j} \tag{27}$$

$$FC_{approach} = AFBR_{approach} \times AD_{A} \times \mathrm{N_j} \tag{28}$$

$$CO_2Emission_{take-off} = AD_{TOFF} \times EI \times \mathrm{N_j} \tag{29}$$

$$CO_2Emission_{climb-out} = AD_{CO} \times EI \times \mathrm{N_j} \tag{30}$$

$$CO_2Emission_{approach} = AD_{A} \times EI \times \mathrm{N_j} \tag{31}$$

Where; FBR: Average Fuel Burn Rate according to WTC (kg per second),

D_{CO}: Average Duration of Climb-out at the selected airport (seconds),

D_{TOFF}: Average Duration of take-off at the selected airport (seconds),

D_A: Average Duration of approach at the selected airport (seconds),

FC: Fuel consumption (kg),

EI: Emission Index (kg per second)

N_j: number of engines used on aircraft type j

Comparison of the take-off, climb-out and approach emission calculated from the operational data, the suggested methodology and ICAO option B method

The emission from take-off, climb-out and approach phases were calculated using actual raw data, the suggested methodology and the ICAO option B method. The three results were compared with each other in each phase.

3.7.4 APU operation

Most airlines do not have a track of their flights' APU operation. When there is very little information available to calculate APU emission, Airport Air Quality manual of ICAO suggests to use the simple approach to calculate the CO_2 emission of APU. Furthermore, the method assumes that short-haul aircraft operates APU for 45 minutes whereas long-haul aircraft operates APU for 75 minutes[39]. According to this guidance manual, it defines short-haul and long-haul flights. The long-haul group include aircraft capable of a maximum range of more than 8 000 km such as A330, A340, A380, B747, B767-200ER, B763, B764, B777 and IL 96 [39] while all the other aircraft belong to Short-haul category. The same assumption was adopted to calculate fuel consumption and CO_2 emission from APUs at the selected airport. The fuel consumption of the APU is calculated using Equation 32. The fuel flow rate of APU according to the aircraft type was obtained from the ACERT tool. Then the CO_2 emission was calculated multiplying the ICAO suggested time with the Emission Factor which was obtained from the ACERT tool according to the type of the aircraft. Equation 33 was used for this emission calculation.

$$FC_{APU} = FFR_{aircraft\ type} \times D_{short/longhaul} \tag{32}$$

$$CO_2Emission_{(APU)} = EF_{aircraft\ type} \times D_{short/longhaul} \tag{33}$$

Where; FC: Fuel consumption (kg),

FFR: Fuel Flow Rate according to aircraft type (kg per minute),
D: Duration of APU operation (minutes),
EF: Emission Factor according to aircraft type (kg per minute).

3.8 Estimating emission due to delay within the LTO cycle

Generally, when the same runway is used for both arrival and departure, arrival flights receive priority over departure flights since the airborne delay is more costly and riskier compared to ground delays [75]. The tower controllers of the airport issue clearance for take-offs during the gaps in the arrivals. Therefore, departure flights spend more time in the taxiing phase compared to arrival flight.

When considering flight delays at movement area; the gates, apron area, taxiways and runways are the areas where congestion could occur. A departure flight has to be in queues for the push back clearance at the gate as well as the departure clearance at runway entrance. Even though engines are not switched on when waiting for the push back clearance, APU of aircraft is operating and it consumes additional fuel for idling. When an aircraft is waiting for take-off clearance at the runway entrance with its engines on, it consumes additional fuel for idling.

Figure 3.3 indicates growth rates of different phases at US domestic aviation. The highest growth rate is indicated by the taxiing phase and with the rapid future demand, this growth rate can be increased. It is proved that the growth rate of the total taxiing time has been greater than the growth rate of airborne time[76]. With these results, it can be assumed that there will be more delays at the taxiing phase causing for more excess fuel waste and more environmental influence. Therefore, the delays at the taxiing operations cannot be ignored since it significantly influences the local air quality. By evaluating the excess fuel and emission due to delays at the taxiing phase, airlines can identify their excess fuel waste and initiate methods to reduce that wastage. The airlines can identify the emission level that they are responsible for due to this fuel waste generated through taxiing delays.

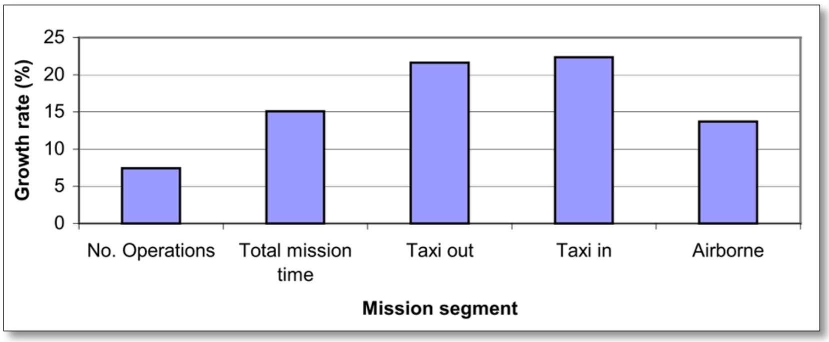


Figure 3.3: Growth rates in US domestic aviation 1995- 2000
Source: 'Constraints in aviation infrastructure and surface aircraft emissions', B. Miller, J. Clarke, K. Minogue, 2001

3.8.1 Delays at the taxiing phase

Unimpeded taxiing time is defined as the time spent for taxiing when there is no congestion or any interference. Taxiing delay can be defined as the additional waiting time compared to unimpeded taxiing time. This situation occurs when the current arrival/departure demand exceeding the arrival/departure capacity of the airfield components. While airlines buffer delay in their schedules, the true delay compared to unimpeded operation time is considerably higher.

The basic method which is recommended by ICAO for using the 20th percentile of actual taxiing time as the unimpeded taxiing time, was selected for this research since this method is the industry practice[77]. After calculating actual taxiing time, the ICAO approach was followed to calculate unimpeded taxiing time. Once the taxiing time distribution was calculated with sorting from the shortest time to the longest time, the 20th percentile of the distribution from the observed values were selected as the unimpeded taxiing time following the industry practices. 3 unimpeded taxiing in times for arrivals and 3 unimpeded taxiing out time for departures were obtained according to the WTC.

Then the delay at the taxiing phase was estimated using the difference between actual taxiing time and the unimpeded taxiing time. Equation 32 and 33 indicate the delay calculation at the taxiing phase.

$$Delay_{taxi-out} = AD_{Taxiing-out} - UD_{taxiing-out} \tag{32}$$

$$Delay_{taxi-in} = AD_{Taxiing-in} - UD_{Taxiing-in} \tag{33}$$

Where; AD: Actual Duration of taxiing in and out (minutes),
UD: Unimpeded Duration of taxiing in and out (minutes).

The delay was converted to excess fuel consumption. The ACERT tool was used to obtain fuel flow rate at the taxiing phase according aircraft type. Equation 34 was used to calculate additional fuel usage per flight.

$$FC = TD \times FFR \tag{34}$$

Where; FC: Fuel Consumption (kg),
TD: taxiing delay (minutes),
FFR: Fuel Flow Rate at taxiing according to aircraft type (kg per minute).

The delay was converted to CO_2 emission. ACERT tool was used to obtain Emission Factor at taxiing according to different types of aircraft. Equation 35 was used to calculate CO_2 emission due to delay per flight at the taxiing phase.

$$\mathrm{CO_2\ Emission} = \mathrm{EF} \times \mathrm{TD} \tag{35}$$

Where; EF: Emission Factor according to aircraft type (kg per minute),
TD: taxiing delay (minutes).

4. DATA ANALYSIS AND RESULTS

4.1 Case study airport- Bandaranaike International Airport (BIA)

Bandaranayake International airport (BIA) in Sri Lanka was taken as the case study for the development of the methodology. Bandaranaike International Airport (IATA: CMB, ICAO: VCBI) is the main international airport serving Sri Lanka. Being an ideal capacity constrained airport, BIA presently handles over 9.8 million passengers per annum, although the designed handling capacity of the terminal building stands at 6 million [78][79]. With the rapid growth in air traffic volume, BIA and airspace system are under increasing pressure.

BIA consists with 5 taxiways (A, B, C, D and E) TWY A and E are situated 120m from runway Centre line while taxiways B, C and D are situated 90m away from runway centerline. BIA operates 24 hours and the runway 04/22 is closed from 0845 to 1115 (GMT) on every Wednesday for maintenance. BIA connects Sri Lanka to the world with 41 airlines (scheduled and seasonal/charter operations) operating to 63 destinations[79].

4.2 Summary of methodology

The Civil Aviation Authority of Sri Lanka, Air Traffic Controllers – Sri Lanka, Airport and Aviation Services (Sri Lanka) and Sri Lankan Airlines were supported in data collection, interviews and field visits.

The mean time spent on different phases within the LTO cycle at BIA were estimated. Those durations were compared with ICAO recommended mean values. BIA specific mean values were used to calculate CO_2 emission at different phases within the LTO at BIA. The results of suggested methodology for calculating CO_2 emission were compared with the results of ICAO CO_2 emission calculation method. The delays at the taxiing phase were estimated. Then the CO_2 emission aroused due to delay was calculated.

4.3 CO_2 emission under different phases of flight at BIA

According to the availability of data at BIA, some phases within the LTO cycle were merged and calculated fuel consumption and CO_2 emission of merged phases. Figure 4.1 demonstrates how phases of flight were merged for this study. For an illustration, time spent in the pushback process is not recorded at DAMR. Therefore, it is assumed that pushback is a part of taxiing out phase.

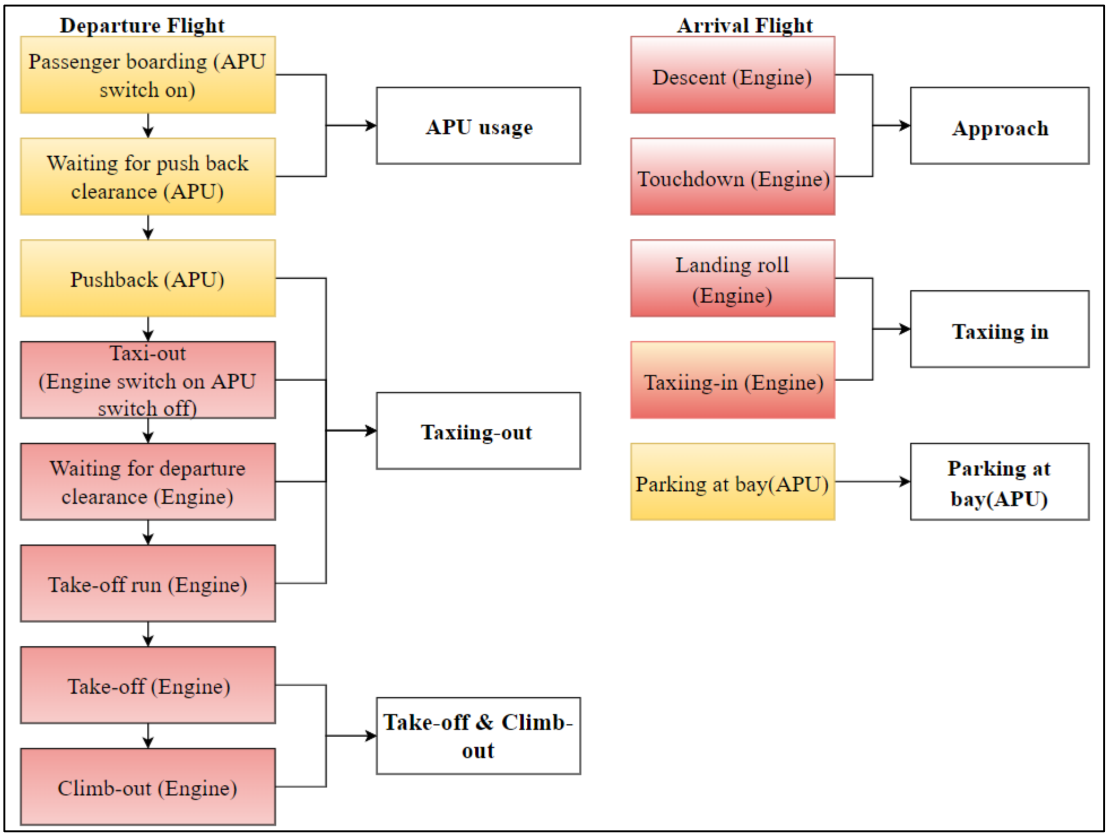


Figure 4.1: Phases of flight within the LTO cycle

4.4 Taxiing phase

4.4.1 Overview of the sample of data analyzed in the taxiing phase

Flights operated at BIA in January, February and March 2018, were observed for this study. The relevant data was obtained from the Daily Aircraft Movement Record (DAMR) which is maintained by Air Traffic Controllers (ATC) Sri Lanka. ATC- Sri Lanka maintains this record for each scheduled and non-scheduled flight that use BIA runway. It tracks the aircraft and records the time of the flight at specific places at the airport. BIA runway handles average 204 flights per day. The obtained sample contained records of 18394 arrival and departure operations. Even though, only 3 months data were received for this study, ATC tracks and records all the flights movements of ground operation at BIA. Since BIA has one runway to handle both arrivals and departures, the observed data were categorized under arrivals and departure flights. Then the flight data were further categorized under the heavy, medium and light aircraft category. Figure 4.2 depicts the percentages of all flights observed within 3 months and these data were analyzed in the taxiing phase and the turnaround. The flight percentages for 3 months were similar according to the available data and it is assumed that the flight percentages are similar throughout the year.

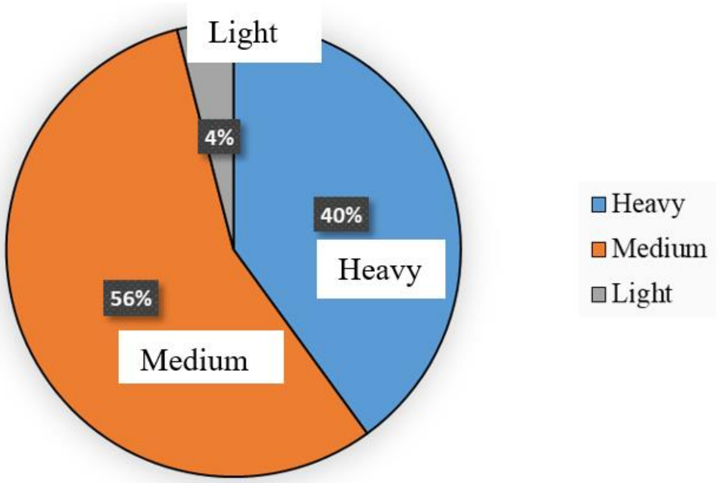


Figure 4.2: Sample size for the analysis of taxiing phase

After calculating actual taxiing times separately for arrivals and departures, it was subcategorized according to the ICAO Wake Turbulence Category (WTC) (heavy, medium and light), the day of the week (Monday to Sunday) and the parking apron (A, B, C and D). Figure 4.3 indicates the taxiing-in time distribution of arrival flights according to WTC.

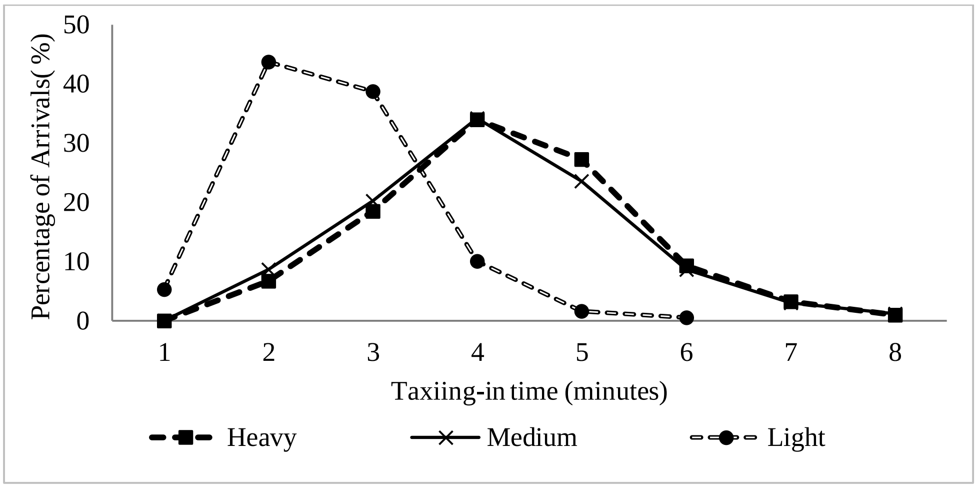


Figure 4.3: Taxiing-in time distribution of arrivals according to aircraft type

4.4.2 ANOVA test results under the category of WTC for Arrivals

ANOVA test is conducted to different distributions separately in order to identify whether this data set can be considered as a part of the population. ANOVA test was conducted under different categories to identify all the sample means within the group are equal or the factor (WTC) did not have any significant effect on the taxiing in time. The null hypothesis states that all the sample means are equal or the factor did not have any significant effect on the results. Whereas, the alternate hypothesis states that at least one of the sample means is different from another. Table 4.1 indicates the ANOVA test results for arrivals under WTC. The distributions of taxiing in time of heavy, medium and light aircraft were tested.

Table 4.1: ANOVA single factor analysis of arrivals under WTC

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	292.46	2	146.23	99.03	0	2.99
Within Groups	4308.67	2918	1.48			
Total	4601.13	2920				

According to Table 4.1, F-value is greater than the F-critical value for the selected alpha level of 0.05 and P-value is less than 0.05. Therefore, the null hypothesis can be rejected and the factor WTC has an influence on the taxiing in time. At least one of the three samples has significantly different mean and thus belongs to an entirely different population. The t-Test was used pairwise to check which samples had different means.

Table 4.2: t-Test results of two samples assuming equal variances

	Heavy	Medium	Medium	Light	Heavy	Light
Mean	4.18	4.12	4.12	2.56	4.18	2.56
Variance	1.31	1.65	1.65	0.56	1.31	0.56
Observations	1175	1625	1625	118	1175	118
Pooled Variance	1.51		1.58		1.24	
Hypothesized Mean Difference	0		0		0	
df	2798		1741		1291	

t Stat	1.19		13.02		14.99	
P(T<=t) one-tail	0.12		2.39E-37		2.66E-47	
t Critical one-tail	1.65		1.65		1.65	
P(T<=t) two-tail	0.23		4.78E-37		5.32E-47	
t Critical two-tail	1.96		1.96		1.96	

Table 4.2 indicates t-Test results among 3 distributions in order to identify the exact distribution that deviates from other distributions. According to Table 6, the p-value of the Heavy vs. Light group and the Medium vs. Light group are less than the selected alpha level (alpha = 0.05). Therefore, the group Heavy vs. Light and the group Medium vs. Light have less than 5% chance of belonging to the same population. The group Medium vs. Heavy has a p-value that is much greater than the significance level (0.05) and it says distribution of heavy and medium aircraft belong to the same population. According to the results, it is clear that the arrivals of light aircraft belong to an entirely different population and had a significant effect on the taxi-in time.

Figure 4.4 indicates the taxiing-out time distribution of departure flights according to WTC.

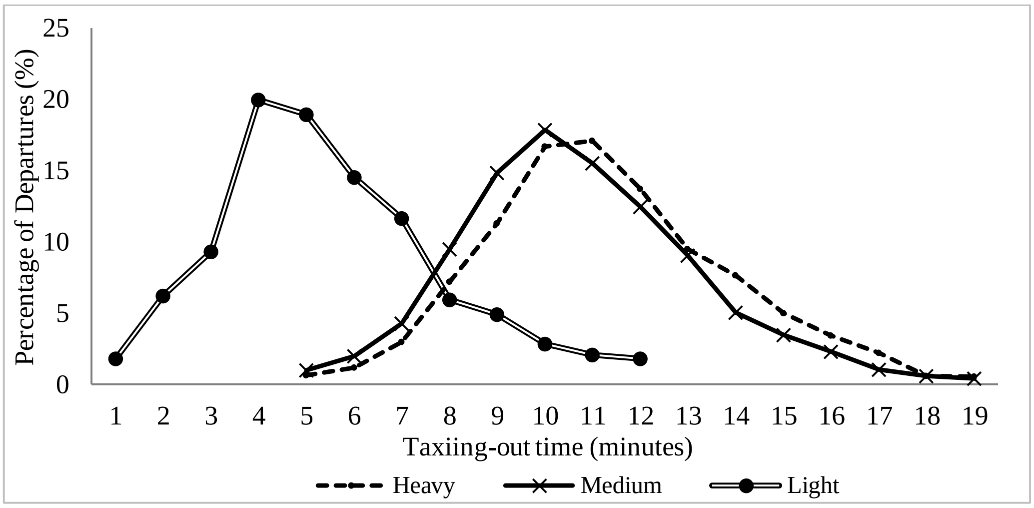


Figure 4.4: Taxiing-out time distribution of departures according to aircraft type

4.4.3 ANOVA test results under the category of WTC-Departures

Table 4.3 indicates the ANOVA test results for departures under WTC. The distributions of taxiing-out time of heavy, medium and light aircraft were tested. According to table 7, the F-value is greater than the F-critical value for the alpha level selected (0.05) and P-value is also less than the alpha level (0.05) selected. Therefore, the null hypothesis can be rejected and at least one of the three samples has significantly different mean and thus belongs to an entirely different population. The factor WTC has a significant influence on the taxiing out time. The t-Test was used pairwise to check which samples had different means.

Table 4.3: ANOVA single factor analysis of departures under WTC

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3150.57	2	1575.29	209.83	4.67E-86	2.99
Within Groups	22679.76	3021	7.51			
Total	25830.33	3023				

According to Table 4.4, the p-values of Heavy vs. Light group and Medium vs. Light group are less than the selected alpha level (alpha = 0.05). Therefore, the group Heavy vs. Light and the group Medium vs. Light have less than 5% chance of belonging to the same population. The p-value is much greater than the significance level in the group Medium vs. Heavy and it says heavy and medium departures belong to the same population. According to the results, it is clear that the departures of light aircraft belongs to an entirely different population and had a significant effect on the taxi-out time.

Table 4.4: t-Test results of two samples assuming equal variances

	Medium	Heavy	Heavy	Light	Medium	Light
Mean	10.69	10.88	10.88	5.71	10.69	5.71
Variance	7.57	7.52	7.52	6.61	7.57	6.61
Observations	1680	1215	1215	126	1680	126
Pooled Variance	7.55		7.44		7.51	
Hypothesized Mean Difference	0		0		0	
df	2893		1339		1804	

t Stat	-1.80		20.26		19.69	
P(T<=t) one-tail	0.04		3.96E-80		1.06E-78	
t Critical one-tail	1.65		1.65		1.65	
P(T<=t) two-tail	0.07		7.93E-80		2.12E-78	
t Critical two-tail	1.96		1.96		1.96	

Figure 4.5 indicates the taxiing-in time distribution of arrivals flights according to the day of the week.

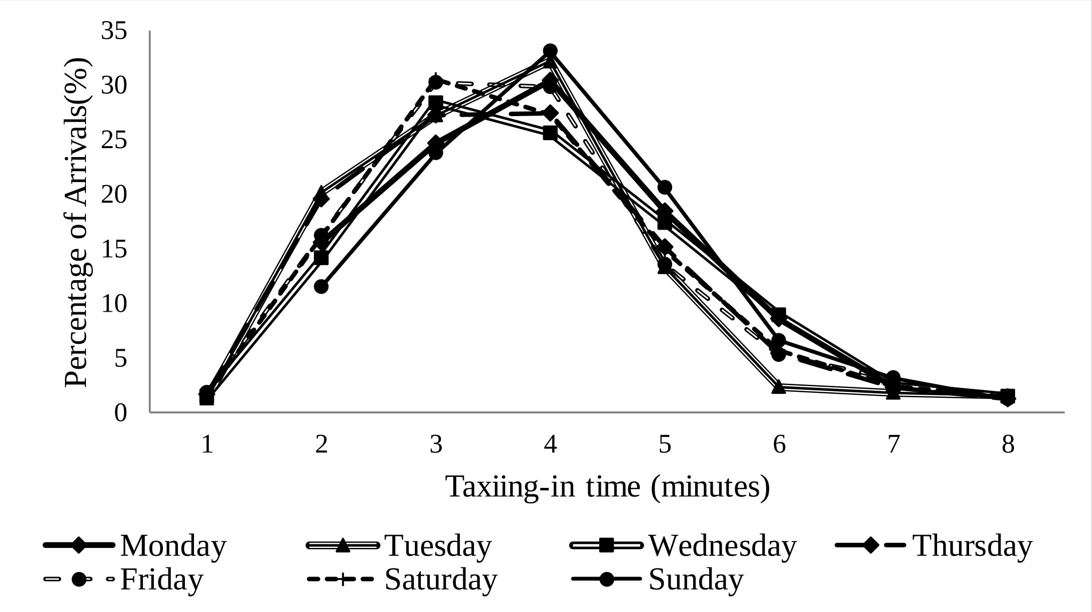


Figure 4.5: Taxiing-in time distribution of arrivals according to the day of the week

4.4.4 ANOVA test results under the category; the days of the week for arrivals

Table 4.5: ANOVA single factor analysis of arrivals under the category of day

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	18.95	6	3.16	1.69	0.12	2.10
Within Groups	5675.12	3032	1.87			
Total	5694.07	3038				

The distributions of taxiing in time of arrivals on Monday, Tuesday, Wednesday, Thursday, Friday, Saturday and Sunday were tested. According to Table 4.5, the F-value is smaller than the F-critical value for the selected alpha level (0.05) and P-value is greater than the alpha level (0.05) selected. Therefore, the null hypothesis can be accepted and sample means are equal and the factor (day) did not have any significant effect on the taxiing in time. Thus, the data set can be considered as a part of the population.

Figure 4.6 indicates the taxiing-in time distribution of arrivals flights according to the day of the week.

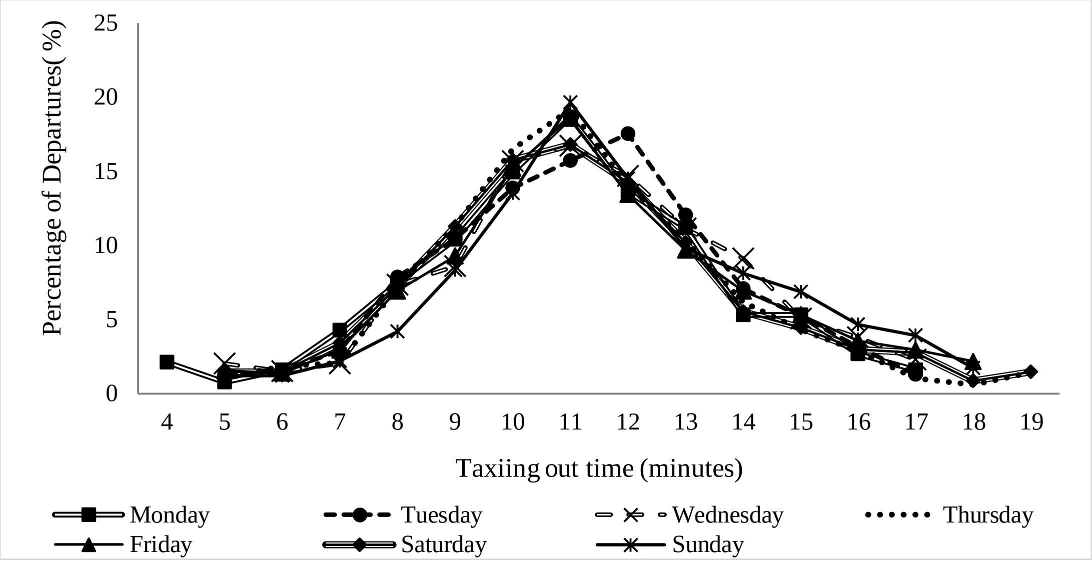


Figure 4.6: taxiing-in time distribution of arrivals according to the day of the week

4.4.5 ANOVA test results under the category; the days of the week for departures

Table 4.6: ANOVA single factor analysis of departures under the category of day

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	85.93	6	14.32	2.07	0.054	2.10
Within Groups	20895.59	3013	6.94			
Total	20981.52	3019				

The distributions of taxiing out time of departures on Monday, Tuesday, Wednesday, Thursday, Friday, Saturday and Sunday were tested. According to Table 4.6, the F-value is smaller than the F-critical value for the selected alpha level (0.05) and P-value is greater than the alpha level (0.05) selected. Therefore, the null hypothesis can be accepted and sample means are equal and the factor (day- Monday, Tuesday, Wednesday, Thursday, Friday, Saturday and Sunday) did not have any significant effect on the taxiing out time. Thus, the data set can be considered as a part of the population.

According to the results, day of the week is not an influencing factor on the taxing time duration at BIA. Minimum variation in the arrival and departure flight schedule at the airport can be attributed for the above finding.

Figure 4.7 indicates the taxiing-in time distribution of Arrivals according to the apron.

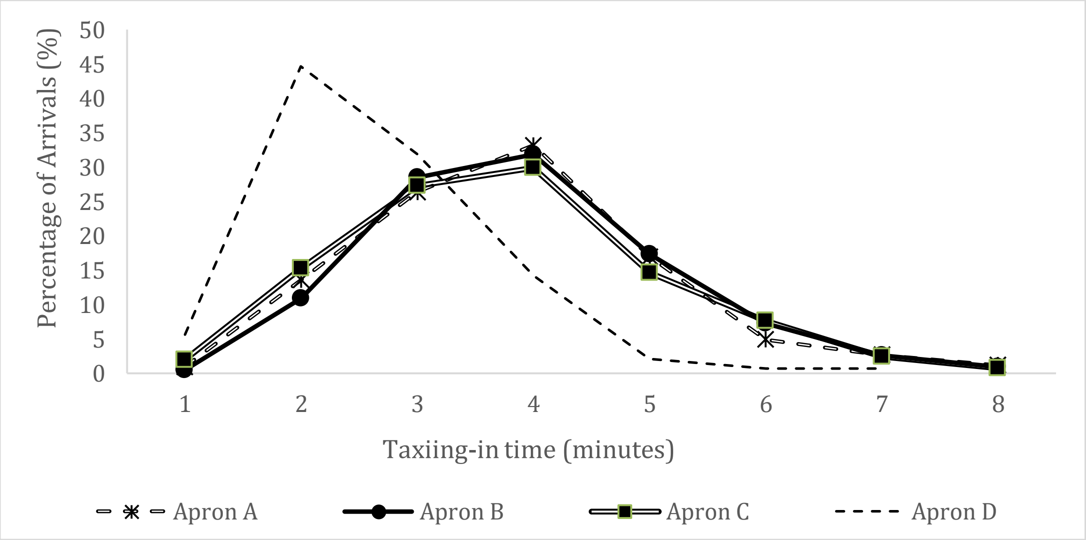


Figure 4.7: Taxiing-in time distribution of arrivals according to the Apron

4.4.6 ANOVA test results under the category; parking apron location for arrivals

Even though BIA has 4 parking aprons, apron D is a remote apron used mostly for domestic light aircraft of 4.1%. Thus, it is removed from this analysis by assuming its impact is insignificant to taxiing time. The distributions of taxiing in time of arrivals at the apron A, B and C were tested.

Table 4.7: ANOVA single factor analysis of arrivals under the category of apron

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7.26	2	3.63	2.13	0.12	2.99
Within Groups	4875.62	2862	1.70			

Total	4882.87	2864				

According to Table 4.7, the F-value is smaller than the F-critical value for the alpha level selected (0.05) and P-value is greater than the alpha level (0.05) selected. Therefore, the null hypothesis can be accepted and sample means are equal and the factor (apron-A, B and C) did not have any significant effect on the taxiing in time. Thus, the data set can be considered as a part of the population.

Figure 4.8 indicates the taxiing-out time distribution of departures according to the apron.

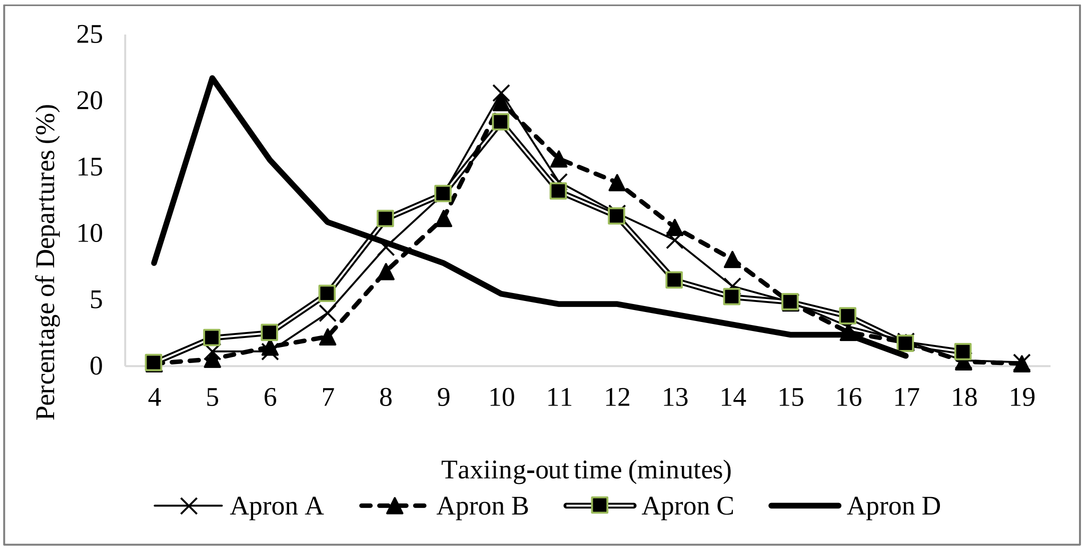


Figure 4.8: Taxiing-out time distribution of departures according to the location of apron

4.4.7 ANOVA test results under the category; parking apron location for departures

The distributions of taxiing out time of departures at the apron A, B and C were tested.

Table 4.8: ANOVA single factor analysis of departures under the category of apron

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	28.38	2	14.19	2.39	0.09	2.99
Within Groups	16421.36	2873	5.92			
Total	16449.74	2875				

According to Table 4.8, the F-value is smaller than the F-critical value for the alpha level selected (0.05) and P-value is greater than the alpha level (0.05) selected. Therefore, the null hypothesis can be accepted and sample means are equal and the factor (apron A, B and C) did not have any significant effect on the taxiing out time. Thus, the data set can be considered as a part of the population.

According to the ANOVA results, the taxiing time distribution according to the location of parking apron did not show statistically significant difference. The taxiing time at BIA does not depend on the factor, the location of parking apron. BIA currently operates with a single pier finger terminal configuration. Thus the layout of apron A, B and C are located close to each other.

According to the ANOVA results, WTC was selected for further analysis as heavy and medium aircraft belong to the same population while light aircraft belong to another population. However, the light aircraft contribution at BIA for the total is 4.1 %. It indicated that average taxing time between heavy and medium aircrafts did not show a statistically significant deviation among them. Table 4.9 gives the estimated TIM parameters for the taxiing phases under different WTC.

Table 4.9: Estimated TIM parameters for taxiing phases

	Mean (minutes)	Standard deviation (Minutes)
Taxiing-in- heavy	4.82	1.22
Taxiing-in- medium	4.56	1.29
Taxiing-out- heavy	10.98	2.81
Taxiing-out- medium	10.08	2.67

4.4.8 Comparison between ICAO recommended values for TIM and estimated average TIM values using operational data

Taxiing-in phase

According to the WTC, the mean taxiing-in times for arrivals were calculated for heavy and medium flights. Figure 4.9 indicates the estimated mean values for the taxiing-in phase of arrivals at BIA. ICAO suggested mean taxiing-in time of 7 minutes indicates in Figure 4.9.

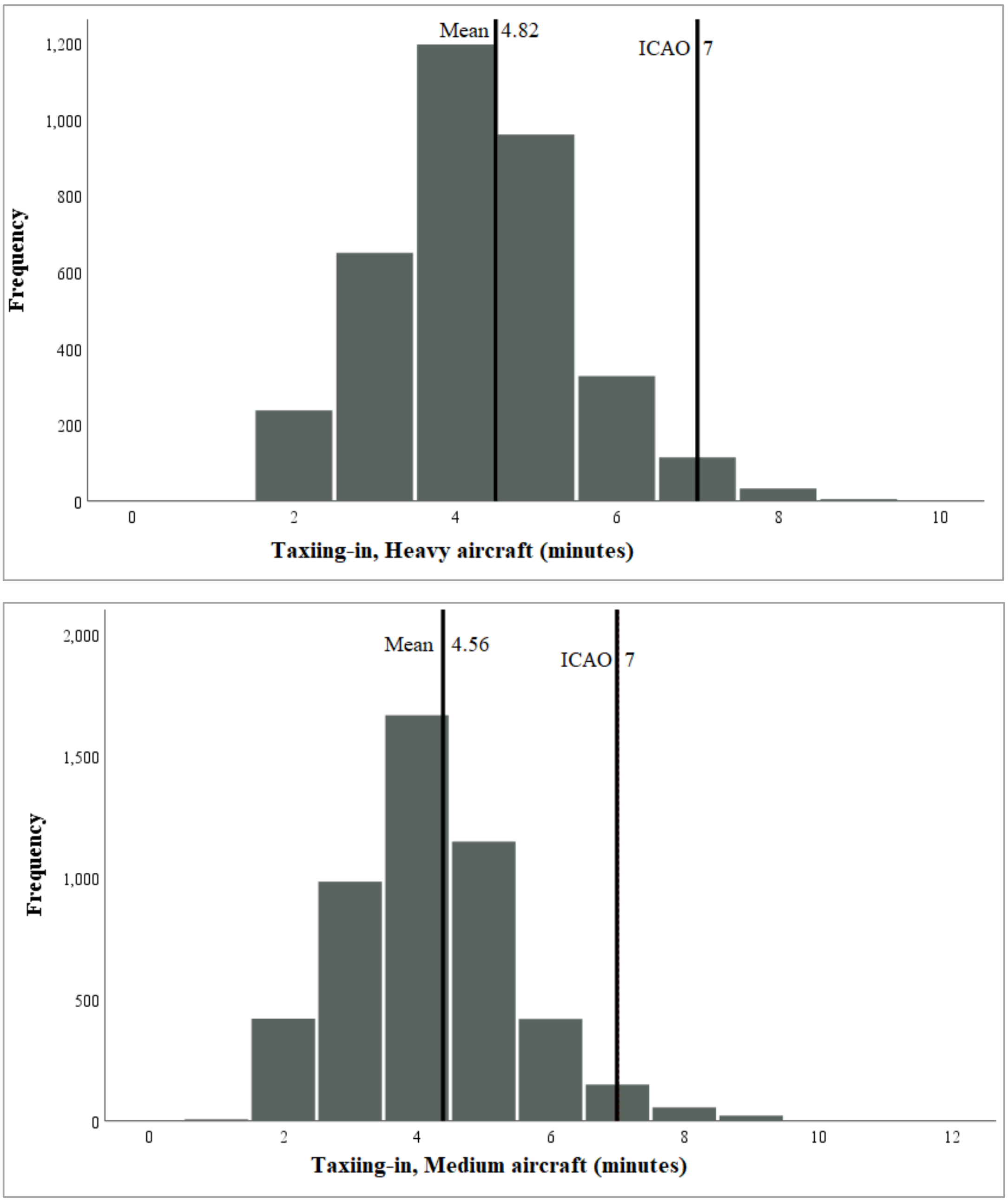


Figure 4.9: Mean taxiing-in time for heavy and medium arrivals at BIA

It is important to determine based on sample data, whether the ICAO recommended value of TIM for taxiing-in phase is significantly different compared to mean taxiing-in at BIA for each WTC. One sample t-Test was conducted to test the difference between the two values.

The One-Sample *t-Test* is used to determine whether the population mean taxiing-in time at BIA (actual operational mean) is statistically different from the ICAO recommended value.

Table 4.10: One-Sample t-Test for mean comparison of taxiing-in phase

Test Value = 7					95% Confidence Interval of the Difference	
Taxi-in time	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Heavy	-131.92	3527	.000	-2.72	-2.76	-2.68
Medium	-151.28	4881	.000	-2.81	-2.85	-2.77

According to Table 4.10, at significance level 0.05, it can be concluded that mean taxiing-in for heavy and medium arrivals at BIA are statistically different compared to ICAO recommended taxiing-in time of 7 minutes, since all the p values are less than 0.05($p< 0.05$). Furthermore, the average operational taxiing-in time according to the WTC are smaller than the ICAO recommended value. Therefore, CO_2 emission level at the taxiing-in phase of BIA will be overestimated by 52% and 45% with the ICAO recommended taxiing-in mean values for medium and heavy categories respectively. Therefore, the fuel consumption and CO_2 emission level at the taxiing in phase of BIA will be overestimated when the ICAO recommended taxiing in mean value is used for estimating GHG levels.

Taxiing-out phase

According to the WTC, mean taxiing-out times for heavy and medium departures were calculated. Figure 4.10 indicates the actual operational values (taxi-out) of departures at BIA. The ICAO suggests mean taxiing-out time of 19 minutes and that value indicates in Figure 4.10.

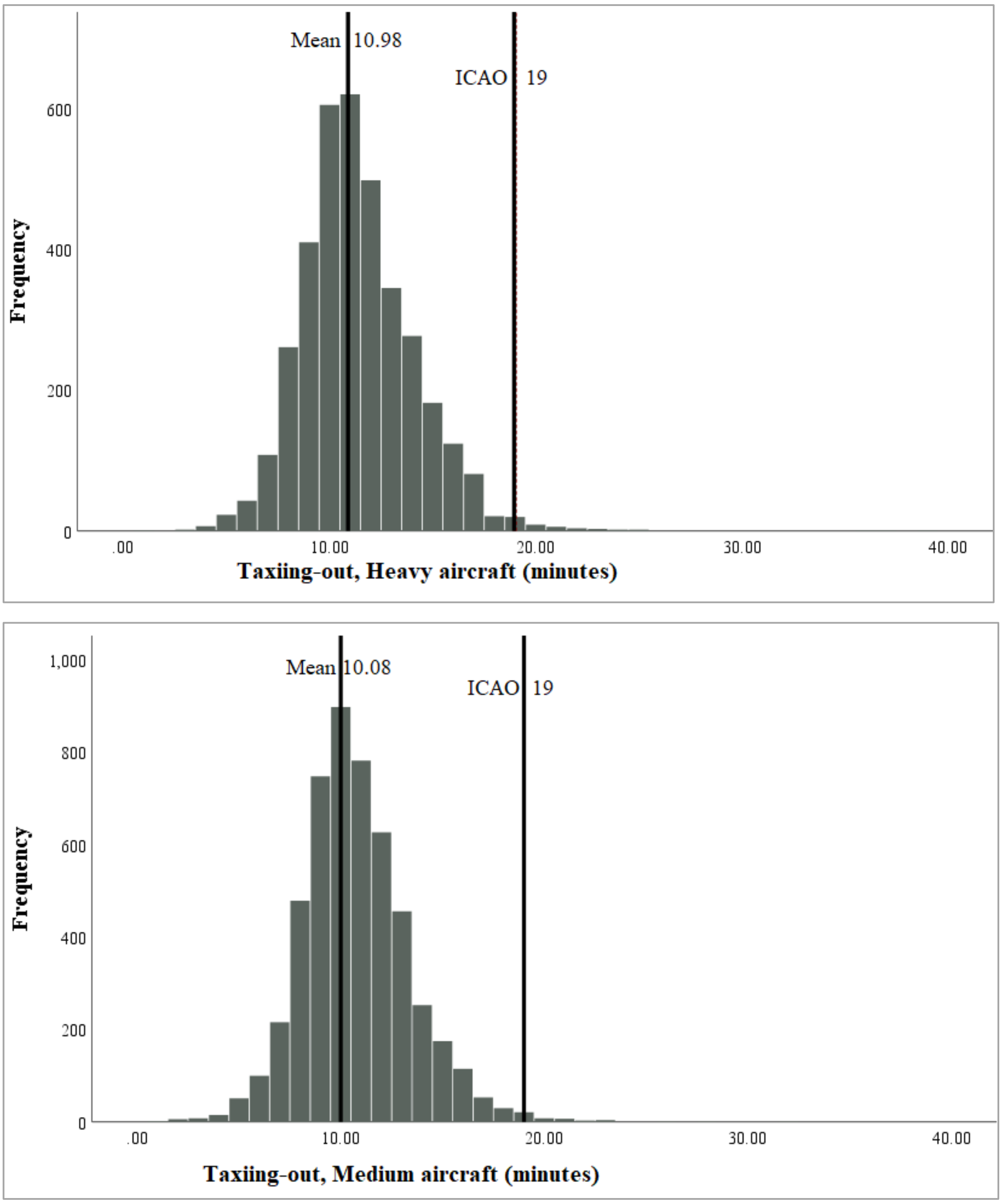


Figure 4.10: Mean taxiing-out time for heavy and medium departures at BIA

It is important to determine based on sample data, whether the ICAO recommended value of TIM for taxiing-out phase is significantly different compared to mean taxiing-out at BIA for each WTC. One sample t-Test was conducted to test the difference between the two values.

The One-Sample *t-Test* is used to determine whether the population mean taxiing-out time at BIA (actual operational mean) is statistically different from the ICAO recommended value.

Table 4.11: One-Sample t-Test for mean comparison of taxiing-out phase

Test Value = 19					95% Confidence Interval of the Difference	
Taxi-out time	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Heavy	-163.588	3656	.000	-7.60459	-7.6957	-7.5135
Medium	-219.619	5059	.000	-8.23696	-8.3105	-8.1634

According to Table 4.11, at significance level 0.05, it can be concluded that mean taxiing-out time for heavy and medium departures at BIA are statistically different compared to ICAO recommended taxiing-out time of 19 minutes, since all the p values are less than 0.05($p < 0.05$). Furthermore, the average operational taxiing-out times according to the WTC are smaller than the ICAO recommended value. Therefore, CO_2 emission level at the taxiing-out phase of BIA will be overestimated by 90% and 74% with the ICAO recommended taxiing-out mean value for medium and heavy categories respectively. Therefore, the fuel consumption and CO_2 emission level at the taxiing-out phase of BIA will be overestimated when the ICAO recommended taxiing-out mean value is used for estimating GHG levels.

4.4.9 Estimation of CO_2 emission level in the taxiing phase

Figure 4.11 indicates CO_2 emission of taxiing in phase of arrivals using operational values, the suggested method and ICAO method. When comparing the results of the operational value method and the suggested method for taxiing-in phase, the results of suggested method 1.6% underestimates the results of actual operation. When comparing the results of the operational value method and the ICAO method for taxiing-in phase, the results of ICAO method 24% overestimates the results of actual operation.

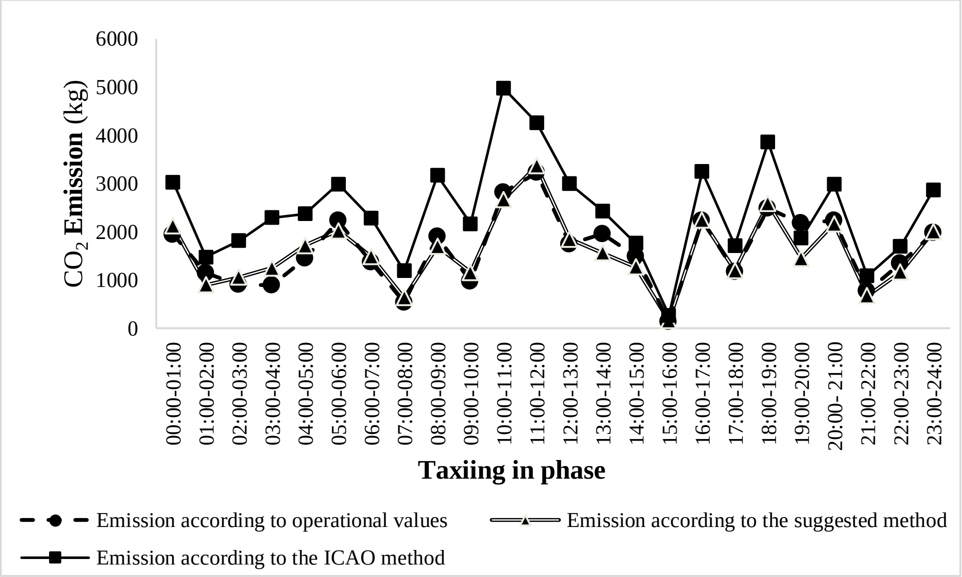


Figure 4.11: Daily taxiing-in emission of arrivals

Figure 4.12 indicates CO_2 emission of taxiing-out phase of departures using operational values, the suggested method and the ICAO method. When comparing the results of operational value method and the suggested method, the results of suggested method 1.5% underestimates the results of actual operation. When comparing the results of operational value method and the ICAO method, the results of ICAO method 71% overestimates the results of actual operation.

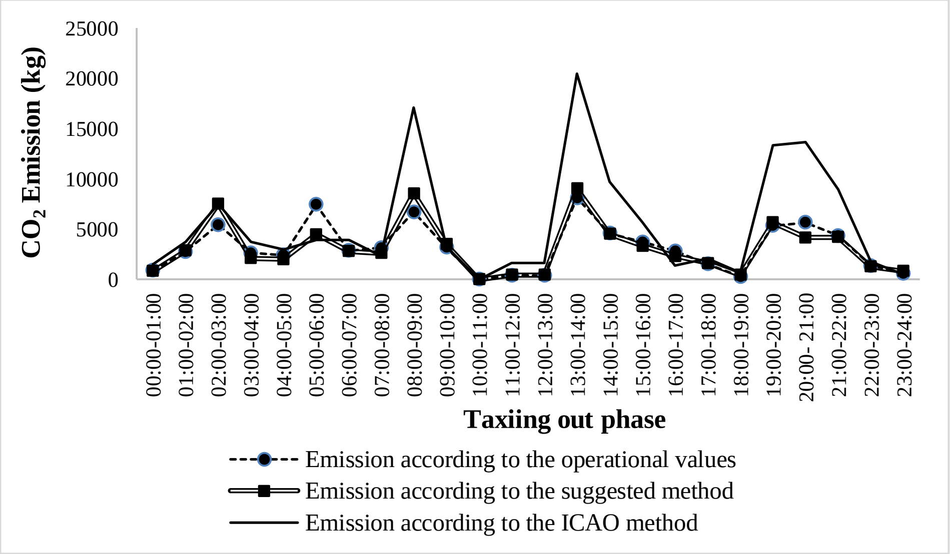


Figure 4.12: Daily taxiing-out emission of departures

4.4.10 Hourly CO_2 emission distribution at the taxiing phase

Once the CO_2 emission was calculated under WTC, CO_2 emission from departures were higher compared to arrivals at the taxiing phase. Among departures, heavy flights had a huge contribution to CO_2 emission due to their long taxiing time. Figure 4.13, 4.14, 4.15 and 4.16 depict the hourly CO_2 emission per operation according to WTC for a particular day of a week. This analysis was conducted to identify the relationship between hourly emission per operation and the number of flights according to WTC within that particular hour. It was needed to identify whether emission per operation increases due to runway congestion.

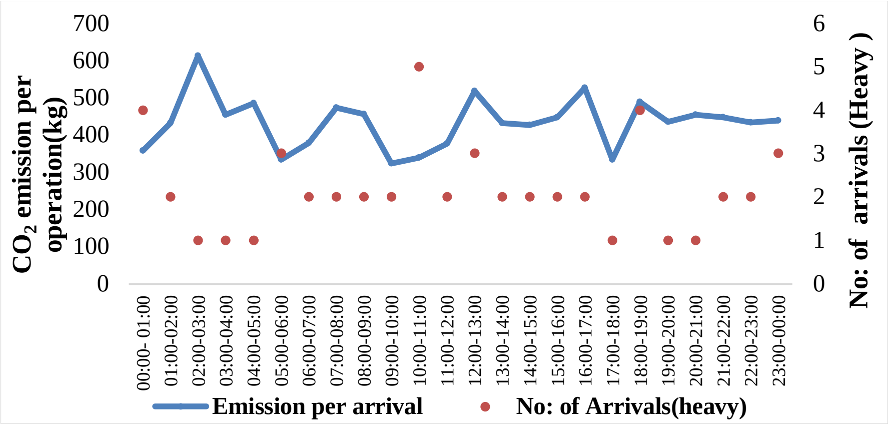


Figure 4.13: CO_2 emission per arrival, heavy aircraft

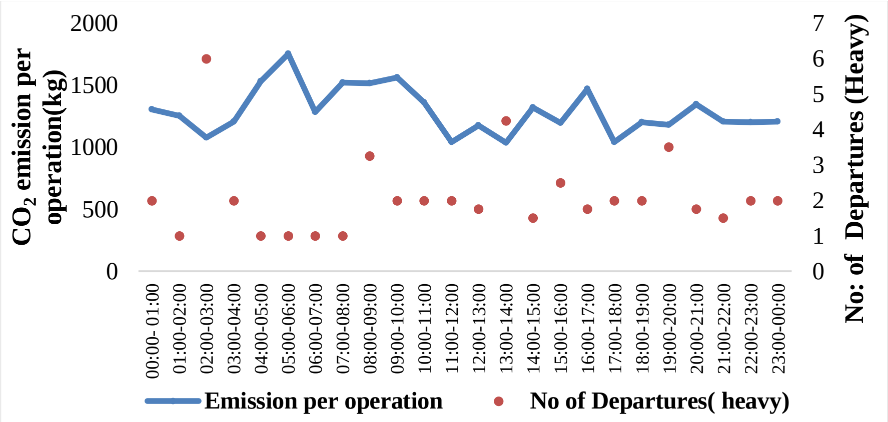


Figure 4.14: CO_2 emission per departure, heavy aircraft

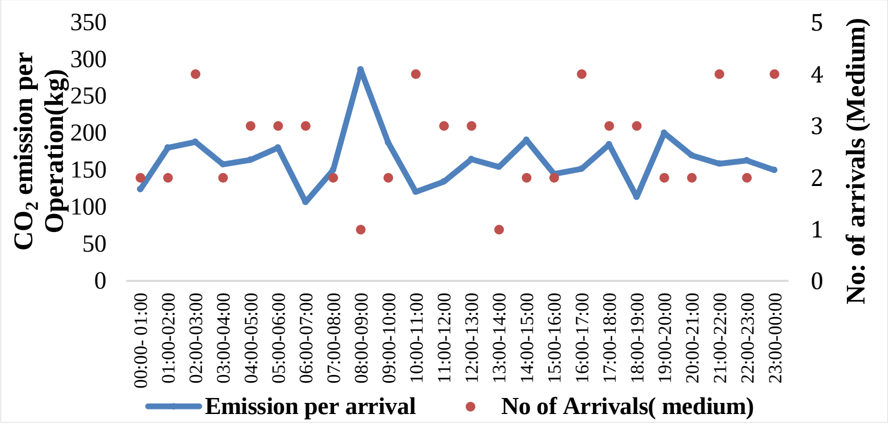


Figure 4.15: CO_2 emission per arrival, medium aircraft

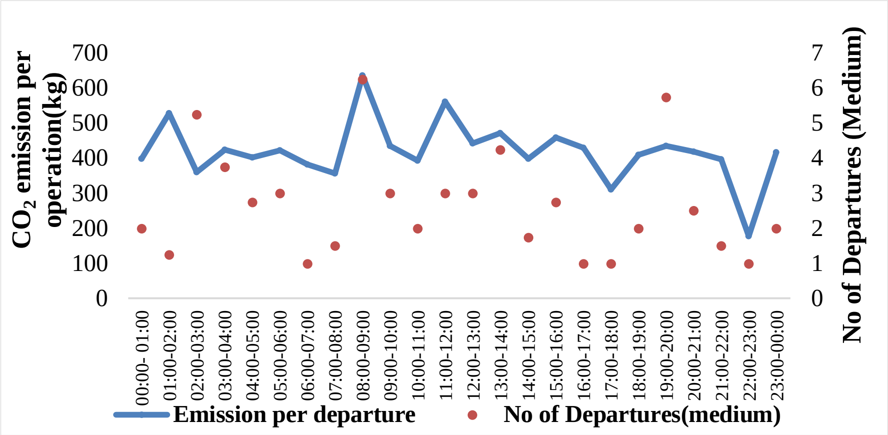


Figure 4.16: CO_2 emission per departure, medium aircraft

Even though it is expected that there may be more emission per operation when there are more flights, it did not appear in the above figures. There are other factors that affect emission per operation. For an illustration, when there are few heavy departures at the runway, it shows a huge emission per operation. Even though there are few heavy departures, there may be more arrivals. Then the departure flights have to do more taxiing by giving the priority to arrivals. In this situation, the number of flights using the runway may be comparatively lower due to few departures but the emission per departure is comparatively higher.

Sometimes there are more heavy arrivals, but still emission per arrival is lower due to the level of runway congestion. This can be expected when there is no obstruction from other medium and light arrivals as well as departures. In this situation the number of flights using the runway may be comparatively higher due to more arrivals but the emission per arrival is comparatively lower. The highest emission per departure appears when there are both arrivals and departures and WTC of the flight also influence for this result.

Since heavy departures have huge CO_2 emission contribution, its emission per operation was compared with arrival rate and departure rate in order to identify whether there is a relationship among these 3 variables. Figure 4.17, the bubble graph indicates the relationship between the arrival rate and departure rate on interest in emission per operation of heavy aircraft. According to the graphs, it can be identified that less consistency in bubble size in certain areas. Therefore, it can be concluded that there is more variation in the relationship between the arrival rate and departure rate on interest in emission per operation of heavy aircraft.

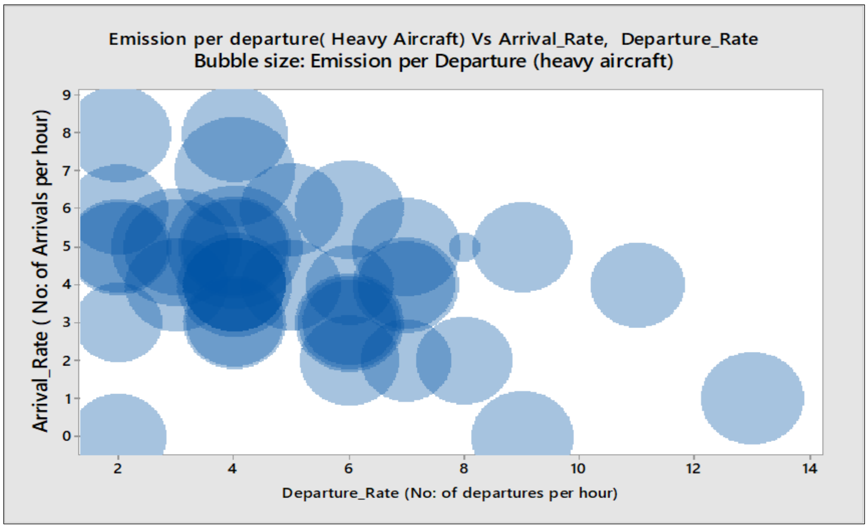


Figure 4.17: The relationship between arrival rate and departure rate on CO_2 emission per operation

4.5 Take-off, Climb-out and approach

4.5.1 Overview of the sample of data analyzed in the Take-off, Climb-out, approach phases

DAMR data keeps track of the aircraft movement only between wheels-on to wheels-off. Other sources of data need to be explored in order to track the movement of the aircraft within the airborne phases (climb-out and approach below 3000ft altitude) of the LTO cycle. This data is recorded in several sources. They include such as data recorded using surveillance equipment (ADS-B and Secondary radar of approach control and tower), electronic flight data strips, on board flight data recorder.

As at present local authority providing air traffic services, Airports and aviation services Ltd (AASL) does not have a data base where data on above phases of flight can be extracted for individual flights operating to BIA. Furthermore, detail records of flight data recorder data is also not possible to be obtained due to airlines policies of confidentiality.

Data obtained from secondary surveillance radar is recorded and kept for a period of 30 days with the navigation service provider. However, data is not organized in a way it can be easily transferred to a data base for analysis. Electronic flight data strips is not in use with the air navigation service provider in Sri Lanka.

Flight data transmitted using ADS-B can be obtained from two sources. ADS-B data is received by the national air navigation service provider and processed for integrating with other surveillance data. ADS-b operates in entire Sri Lankan airspace[56] and real-time data of flights are received. That data can be used to calculate the actual durations of all the phases of flight accurately. This data is only stored for a period of 30minutes due to the high volume of data received and limited storage capacity. Therefore, the data from ATC ground stations cannot be used in this study due to the unavailability of past flight records of Sri Lankan airspace. In order to be used for the above analysis, this raw data need to be specially recorded for a sample period and processed to filter-in the data relevant for the LTO cycle. Even though this is a rich source of data, it was not used due to the unavailability of necessary computing resources and time require to extract the specific portion of climb-out and approach for each flight.

ADS-B data can also be obtained via internet flight tracking service providers who collect, process and store ADS-B data transmitted from aircrafts. These internet service providers can provide useful flight information specifically for an airport or a flight. They make available processed past data covering a specified period and an airport, airline or a flight for a fee (often very expensive) which can be directly downloaded. In order to analyze the CO_2 emission take-off, climb-out and approach, data was extracted using Flightaware.com website. . Data was collected for a duration of one-week in order to obtain a representative sample of observations. All the flights arriving and departing during the week to and from BIA was observed. Available data provides a recorded history of each flight's path from origin to destination. Recorded data includes the variation of speed and altitude with respect to flight time. Number of data points collected was 1354.

Only heavy and medium category aircraft are covered in the data collection due to the small portion (<5%) of light aircraft operations at BIA. Figure 4.18 indicates the data that were used for analysis in the phases of take-off, climb-out and approach.

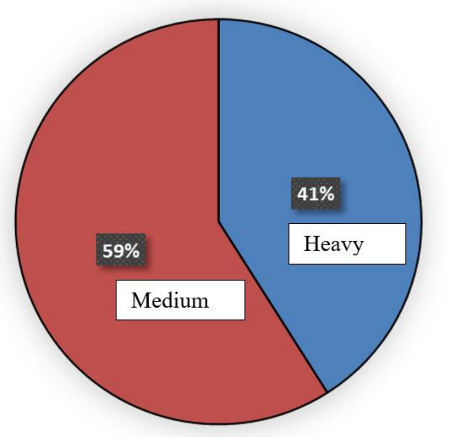


Figure 4.18: Sample size for the analysis of Take-off, climb-out and approach phases

FlightAware does not support to identify the exact duration of take-off and the climb-out phases separately. The take-off phase takes few seconds to complete that phase and reaches the climb-out phase. Therefore, the aggregate duration of take-off and climb-out phases were obtained from the FlightAware.

4.5.2 Fuel consumption and CO_2 emission calculation of Take-off, Climb-out, Approach phases

ICAO DOC 8643- Aircraft Type Designators site for engine type [80]provides the engine type of aircraft. The engine type of the observed flights for this study were identified through this document. EASA maintains ICAO Aircraft Engine Emissions

Databank which provides the fuel rates under different flight phases according to the engine type[38]. With the use of 2 sources Table 4.12 is created for the observed flights at BIA.

Table 4.12: Fuel flow rates at different flight phases according to aircraft type

Type of the aircraft	**Fuel flow rate (kg per second)**		
	Take-off	Climb-out	Approach
A320	1.132	0.935	0.312
A321	1.295	1.058	0.345
B738	0.854	0.714	0.260
B739	0.913	0.761	0.274
DH8D	0.62	0.52	0.19
A332	2.904	2.337	0.744
A333	3.139	2.530	0.821
A346	2.240	1.830	0.620
B744	2.583	2.106	0.685
B763	2.725	2.125	0.718
B772	3.926	2.996	0.979
B77W	4.69	3.67	1.13
B788	2.279	1.874	0.623
B789	2.395	1.966	0.647

4.5.3 Climb-out

ANOVA test results for the data obtained phase climb-out

Table 4.13: ANOVA single factor analysis under climb-out phase

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.19E-05	1	5.19E-05	0.66	0.42	3.86
Within Groups	0.05	675	7.91E-05			
Total	0.05	676				

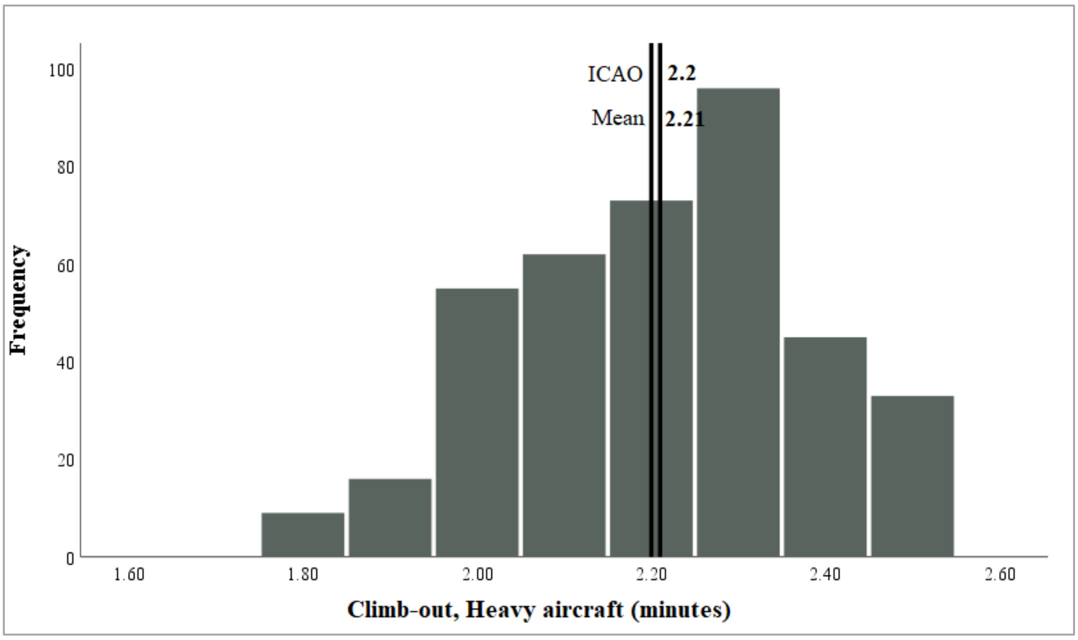
According to Table 4.13, the F-value is smaller than the F-critical value for the alpha level selected (0.05) and P-value is greater than the alpha level (0.05) selected. Therefore, the null hypothesis can be accepted and the factor (heavy, medium) did not have any significant effect on the results (climb-out duration). Table 4.14 gives the estimated TIM parameters for the climb-out phase under different WTC.

Table 4.14: Estimated TIM parameters for climb-out phase

	Mean	Standard deviation
Climb-out- heavy	2.21	0.17
Climb-out- medium	2.06	0.14

Comparison between ICAO recommended values for climb-out and estimated average climb-out using operational data

Figure 4.19 indicates the estimated values using actual operational values for the climb-out phase of heavy and medium aircraft at BIA. The ICAO suggested TIM value for climb-out phase, duration of 2.2 minutes indicates in Figure 4.19.



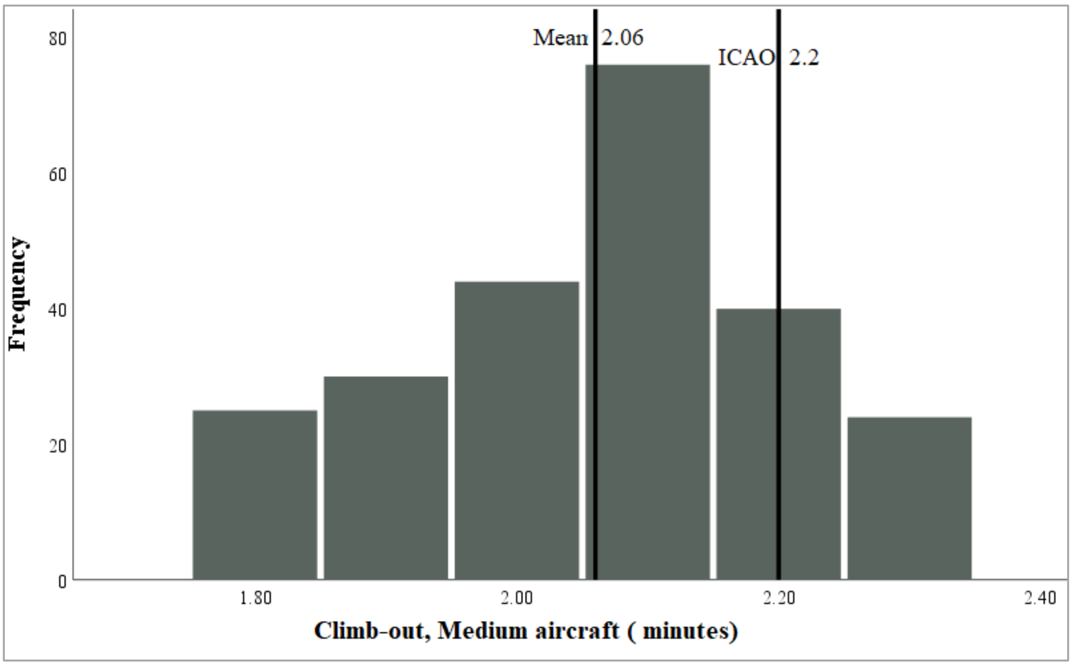


Figure 4.19: Climb-out time distribution of Heavy and medium aircraft at BIA

The mean climb-out durations of BIA did not show a significant deviation from the ICAO recommended climb-out mean values for both medium and heavy categories since the climb-out phase is largely standard process at most international airports.

Estimation of CO_2 emission level from the take-off phase

The operational values of take-off phase for calculating the durations were not tracked by the available technologies at BIA. Therefore the ICAO recommended TIM value for take-off, 0.7 minutes was assumed as the take-off duration of departures at BIA. Figure 4.20 indicates the CO_2 emission level from the take-off phase at BIA.

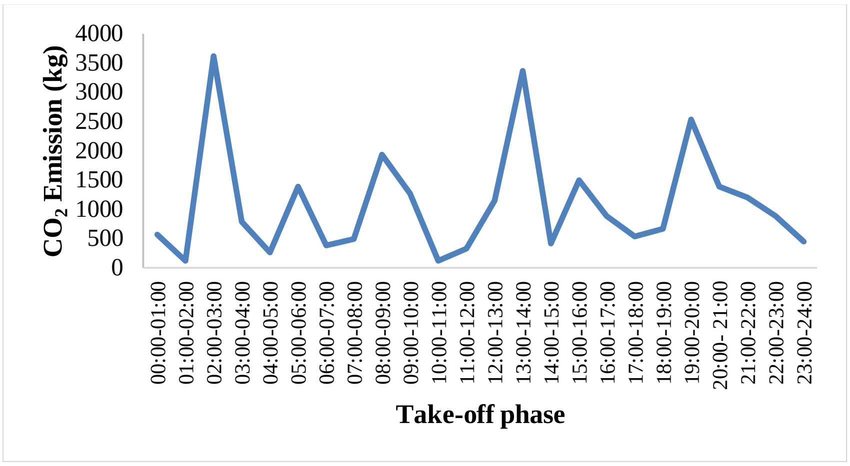


Figure 4.20: Daily CO$_2$ emission from the take-off phase at BIA

Hourly CO$_2$ emission distribution at the take-off phase

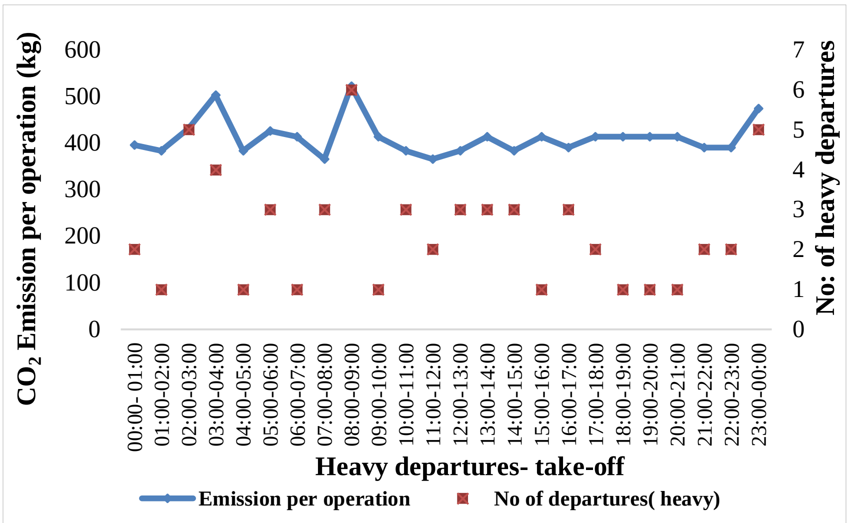


Figure 4.21: Hourly CO$_2$ emission per operation in the take-off phase of heavy departures

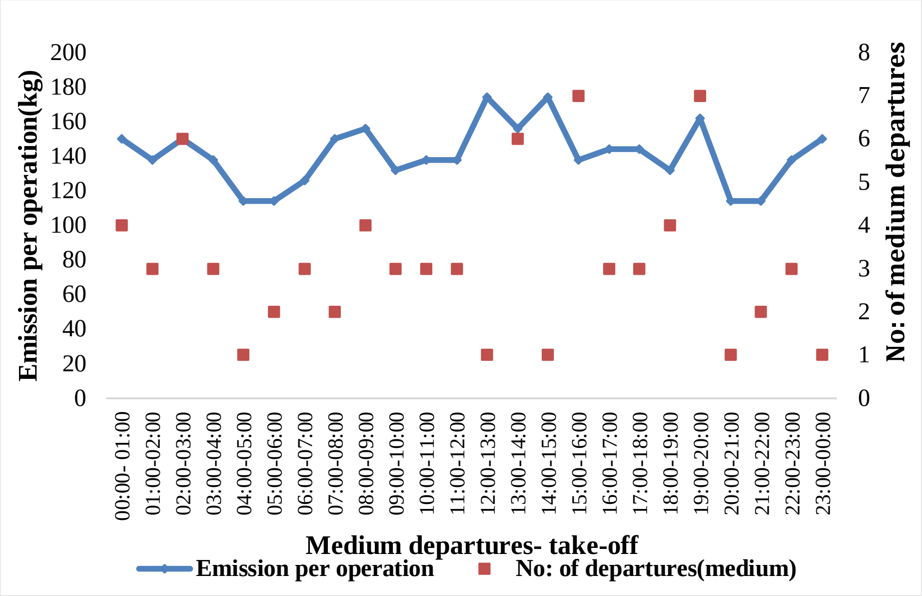


Figure 4.22: Hourly CO_2 emission per operation in the take-off phase of medium departures

Figure 4.21 indicates hourly CO_2 emission per operation at the take-off phase for heavy departures. Figure 4.22 indicates hourly CO_2 emission per operation at the take-off phase for medium departures. The duration of take-off phase is considered as 0.7 minutes for both heavy and medium departures by following the ICAO recommended value. Therefore, the hourly fluctuation does not depend on the duration. It depends on the engine type of the flight. Heavy aircraft's fuel flow rate is significantly higher than medium flights.

Estimation of CO_2 emission level from Climb-out phase

Figure 4.23 indicates hourly CO_2 emission of climb-out phase of arrivals at BIA using operational values and the suggested method. When comparing the results of the suggested method and operational value method for calculating emission for the climb-out phase, the results of suggested method 1.5% underestimates the results of actual operation. When comparing the results of the ICAO method and operational value method for calculating emission for the climb-out phase, the results of ICAO method overestimates the results of actual operation.

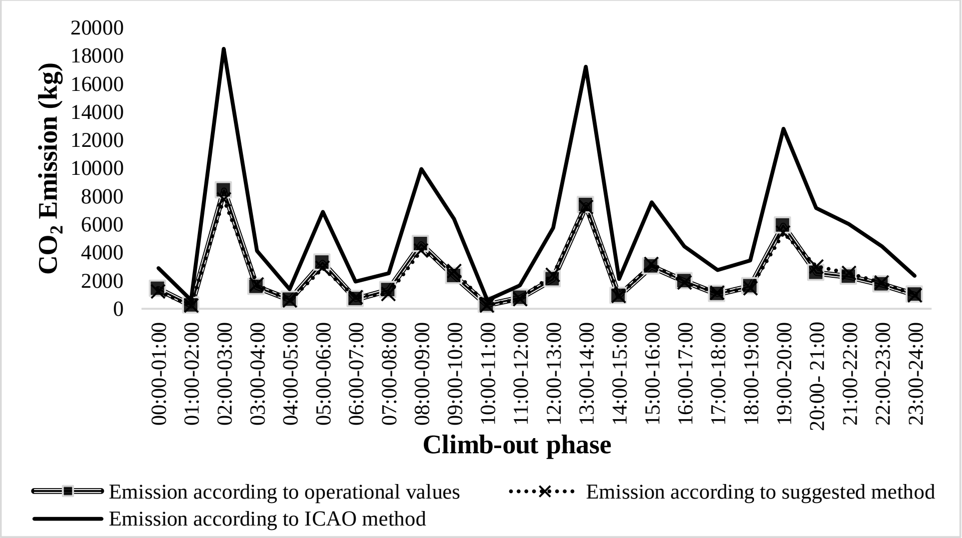


Figure 4.23: Daily CO_2 emission at the Climb-out phase at BIA

Hourly CO_2 emission distribution at the climb-out phase

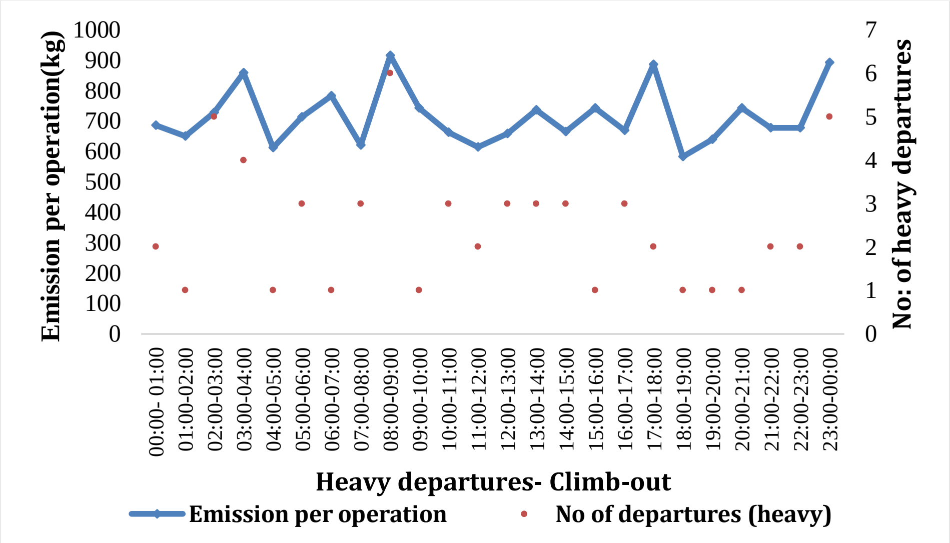


Figure 4.24: Hourly CO_2 emission per operation in the climb-out phase for heavy departures

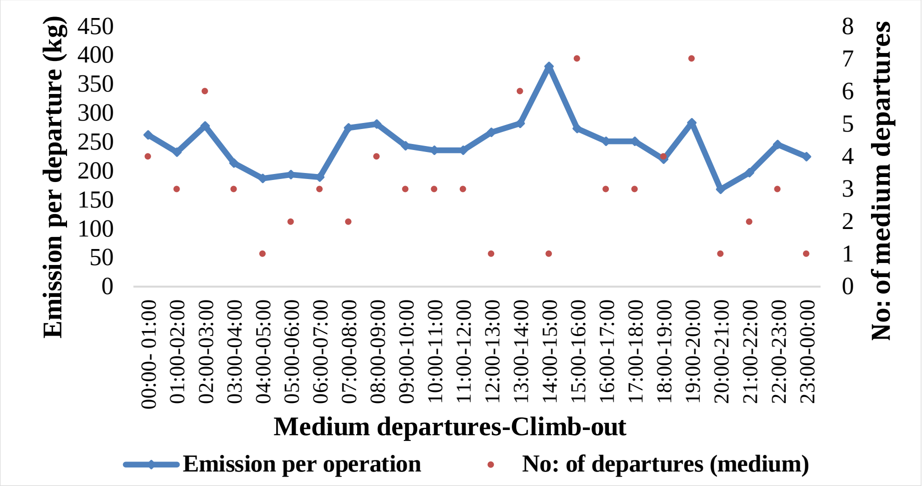


Figure 4.25: Hourly CO_2 emission per operation in the climb-out phase for medium departures

Figure 4.24 indicates hourly CO_2 emission per operation of heavy departures at the climb-out phase. Figure 4.25 indicates hourly CO_2 emission per operation of medium departures at the climb-out phase. Currently at BIA, the duration of climb-out phase depends on the engine type due to less congestion in the climb-out phase. Heavy flights require higher fuel flow rate compared to medium departures in the climb-out phase.

4.5.4 Approach

ANOVA test results for the approach phase

Table 4.15: ANOVA single factor analysis for the approach phase

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.002	1	0.002	2.304	0.129	3.855
Within Groups	0.615	675	0.001			
Total	0.618	676				

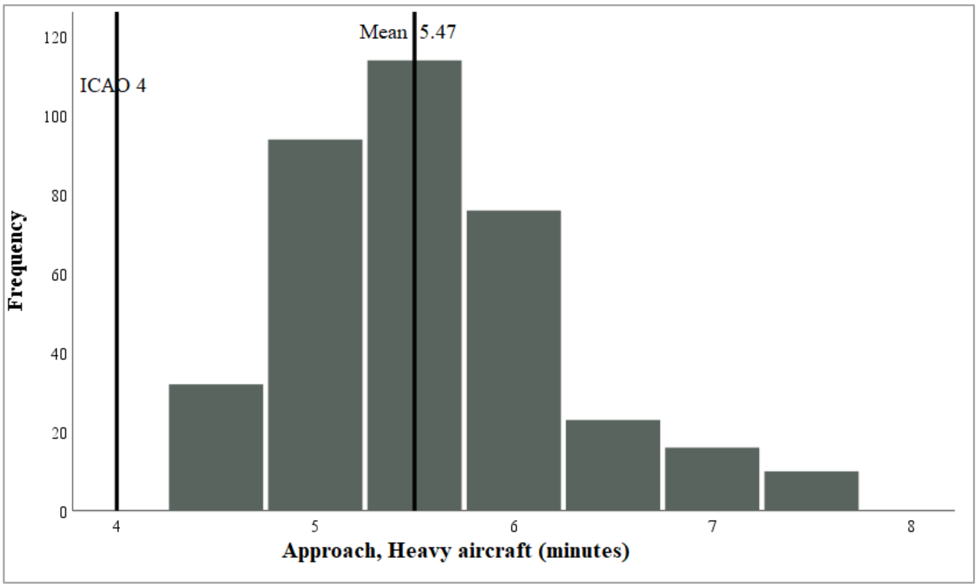
According to Table 4.14, the F-value is smaller than the F-critical value for the alpha level selected (0.05) and P-value is greater than the alpha level (0.05) selected. Therefore, the null hypothesis can be accepted and the factor (heavy and medium aircraft) did not have any significant effect on the results (duration of the approach phase). Table 4.16 gives the estimated TIM parameters for the approach phase under different WTC.

Table 4.16: Estimated TIM parameters for climb-out and approach phases

	Mean	Standard deviation
Approach - heavy	5.47	0.69
Approach- medium	5.65	0.71

Comparison between the ICAO recommended TIM for the approach phase and the estimated average approach time using operational values at BIA

Figure 4.26 indicates mean approach time of heavy and medium aircraft at BIA. The ICAO suggested TIM value for approach time of 4 minutes is indicated in Figure 4.26.



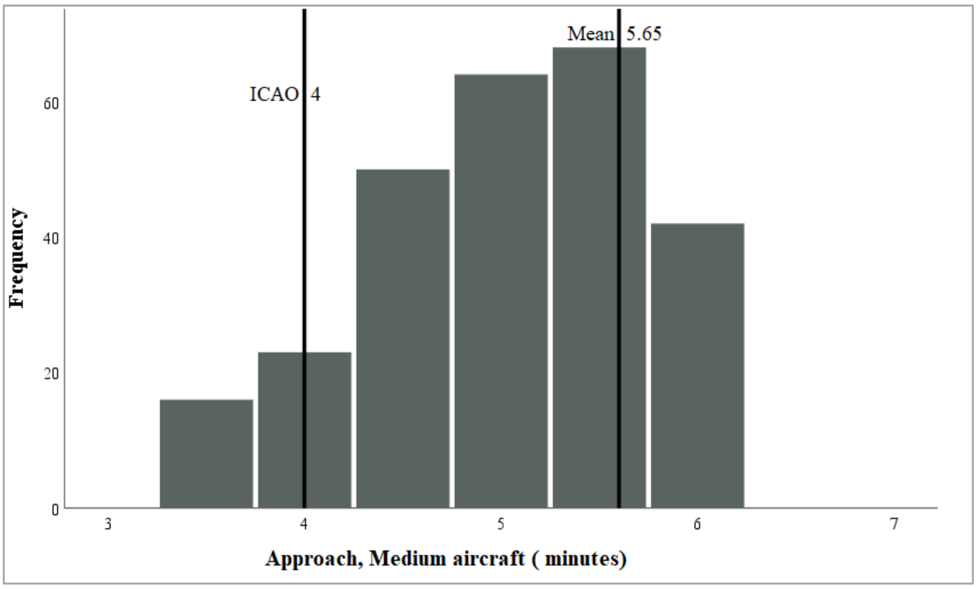


Figure 4.26: Approach time distribution of Heavy and medium aircraft at BIA

One sample t-Test was conducted to identify whether the population mean value of the approach phase is statistically different from the ICAO recommended TIM value of the approach phase.

Table 4.17: One-Sample t Test for mean comparison between estimated approach time and ICAO recommended mean value

One-Sample Test						
	Test Value = 4					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Heavy	26.49	278	.000	1.46	1.35	1.57
Medium	29.29	397	.000	1.68	1.57	1.79

According to Table 4.15, at significance level 0.05, it can be concluded that mean approach time for heavy and medium arrivals at BIA are statistically different compared to ICAO recommended approach time of 4 minutes, since all the p values are less than 0.05($p < 0.05$). However, for the approach phase, results of the one sample t-test indicate that ICAO recommended values are significantly deviated compared to the same parameters estimated using the operational data. Therefore, the fuel consumption and CO_2 emission level at BIA will be underestimated at the approach phase with the ICAO recommended value.

The approach duration was larger than the default. As the approach phase is a largely standard process at most international airports, above significant deviation is an interesting finding. By studying the approach procedure at BIA it can be observed that aircraft are lined up for the final approach at an altitude between 2000 to 1000ft. Hence, there is a variation in the decent path of flights from different directions from 3000ft down to the final approach fix. ICAO defaults values are based on broad industry-wide parameters. The key assumptions that affect the approach time duration such as approach path, flight mix, flight rules, weather etc., are unknown for the ICAO standard values. In this research, one week's data was analyzed for the phases of climb-out and approach. If a large enough representative sample was analyzed a more precise insight on the deviation could be obtained. Aircraft mix is another factor that influences in this difference.

Estimation of CO_2 emission level from the Approach phase

Figure 4.27 indicates hourly CO_2 emission of approach phase of departures at BIA using operational values and the suggested method. When comparing the results of suggested method and actual operational value method for calculating emission for the approach phase, the results of suggested method 4.1% overestimates the results of actual operation. When comparing the results of ICAO method and actual operational value method for calculating emission for the approach phase, the results of ICAO method 27% underestimates the results of actual operation.

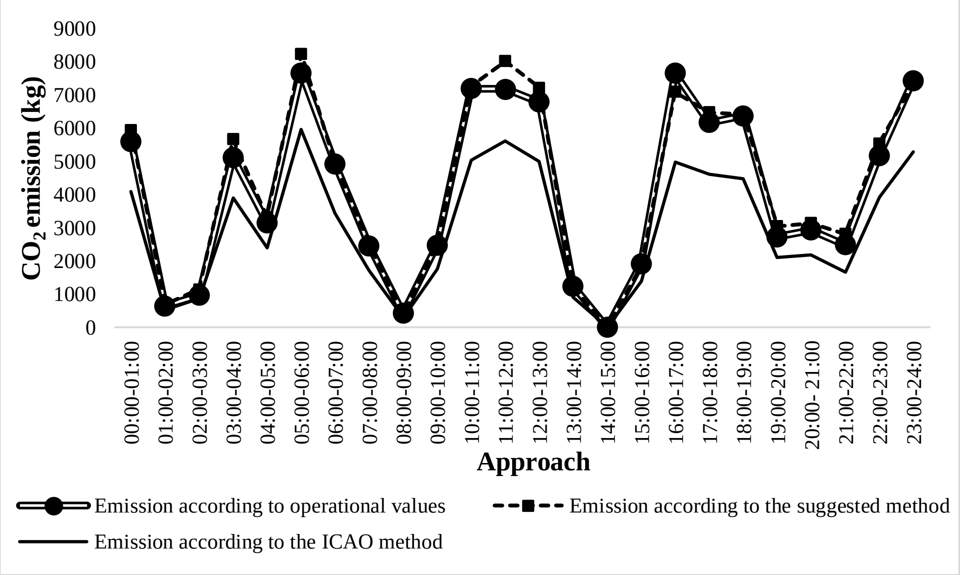


Figure 4.27: Daily CO_2 emission at the approach phase at BIA

Hourly CO_2 emission distribution at the approach phase

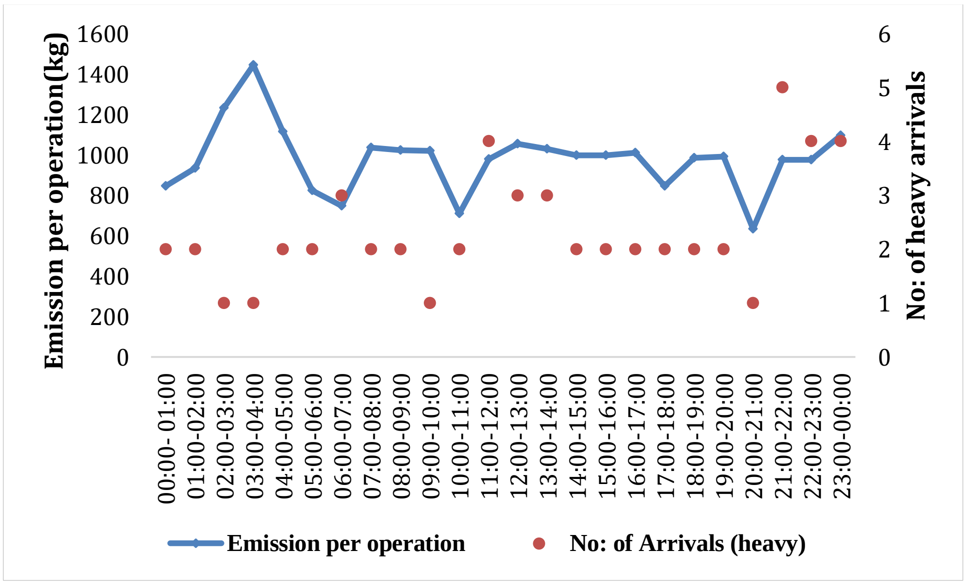


Figure 4.28: Hourly CO_2 emission per operation in the approach phase for heavy arrivals

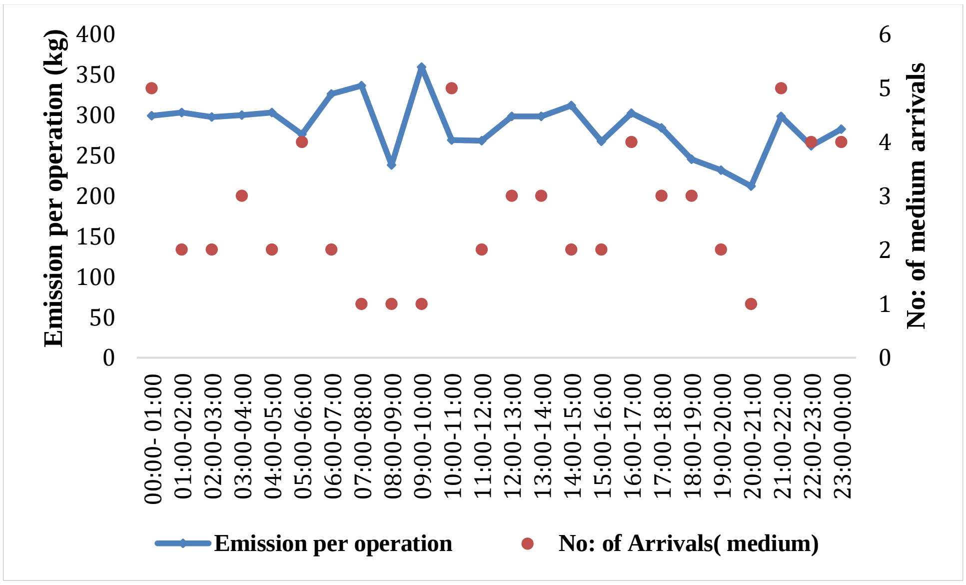


Figure 4.29: Hourly CO_2 emission per operation in the approach phase for medium arrivals

Figure 4.28 indicates hourly CO_2 emission from the approach phase for heavy arrivals. Figure 4.29 indicates hourly CO_2 emission from the approach phase for medium arrivals According to figure 4.28 and 4.29, number of arrivals does not show a significant influence on the emission per operation. In this situation, only the fuel flow rate according to the engine type influences emission per operation since there is no congestion in the approach phase. The fuel flow rate of the heavy flights at the approach phase is significantly higher compared to medium flights. Therefore emission per operation of heavy arrivals is higher medium arrivals in the approach phase.

4.6 Estimating CO_2 emission due to APU usage

The time when aircraft uses its APU at the turnaround phase is not recorded at BIA. Airport Air Quality manual of ICAO suggests to assume that short-haul aircraft operates APU for 45 minutes whereas long-haul aircraft operates APU for 75 minutes within the turnaround of an aircraft. Some aircraft use GPUs instead of APUs. Some aircraft follow different policies when using APU (Operational duration may depend on the airline). Due to the unavailability of recorded data related to APU operation at BIA, the ICAO assumption was applied for this study. Emission factor according to the aircraft type was obtained from ACERT tool. Figure 4.30 depicts the hourly emission per APU operation for a particular day of the week at BIA.

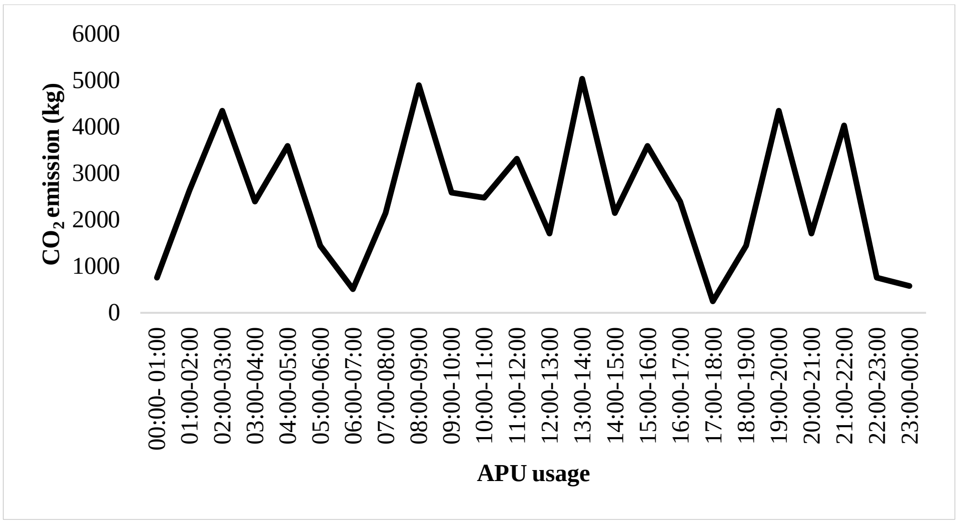


Figure 4.30: Hourly CO_2 emission from APU operation at BIA

The actual emission from APU operation may be under or over estimated by following the ICAO recommended values. According to Figure 4.30, the APU influences the local air quality significantly.

4.7 CO_2 emission per operation within LTO cycle

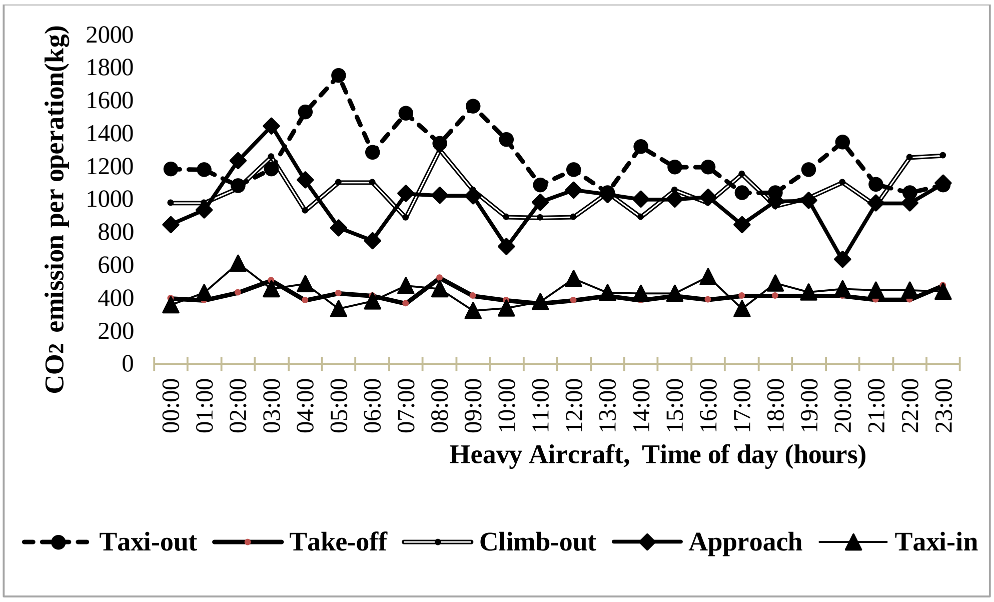


Figure 4.31: CO_2 Emission per operation for heavy flights at BIA

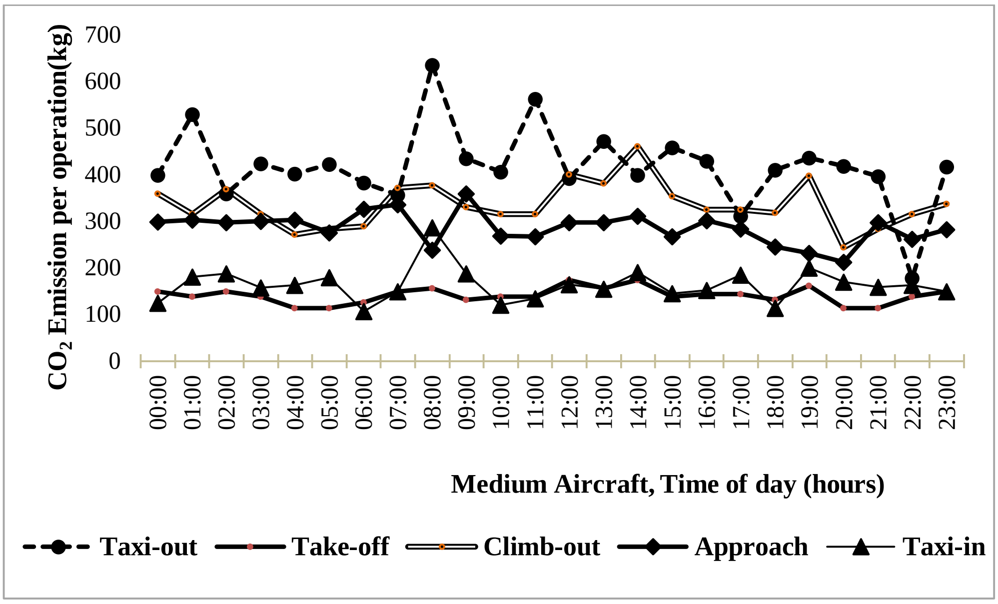


Figure 4.32: CO_2 Emission per operation for medium flights at BIA

Figure 4.31 indicates hourly CO_2 emission per operation of take-off, climb-out, approach, taxiing-in and taxiing-out phases for heavy aircraft. Figure 4.32 indicates hourly CO_2 emission per operation of take-off, climb-out, approach, taxiing-in and taxiing-out phases for medium aircraft.

The take-off phase shows the least CO_2 emission contribution as a result of its lowest operational time in spite of its high fuel flow rate. The taxiing out phase shows the highest CO_2 emission per operation in both heavy and medium flights. Delaying aircraft after push back due to congestion in the apron and taxiways for taxing-out operation is the main reason for higher emission levels in that phase. Analysis in Figure 4.32 and 4.33 can be used to observe where excessive CO_2 emission is taking place compared to a chosen base level. Off-peak emission level per operation can be chosen as the base level to calculate excessive emission. The variation of emission per operation within a given time period depends upon the average time in mode value within that time period and the mix of heavy and medium aircraft operations. Hence, time periods with peak rate of operation resulting causing congestion in airside elements would indicate higher average emission per operation compare to off-peak periods. This can be observed where graph of taxing-out and approach is showing higher variation in emission per operation between different time periods than more standard phases such as take-off and climb out. Thus, the influence of congestion causing excessive emission levels can be clearly observed in the Taxing-out phase during the morning peak periods.

Considering all phases of flight within the LTO, the CO_2 emission level under different phases at BIA were calculated. The percentages of emission under the different phases are indicated in Table 4.18.

Table 4.18: Percentages of emission levels under different phases according to aircraft type

	% of emission from Heavy Aircraft	% of emission from Medium Aircraft
Taxiing-out	30	31
Take-off	10	10
Climb-out	25	25
Approach	24	21
Taxiing-in	11	12

According to Table 4.18, taxiing-out and climb-out phases should be given more priority in reducing emission since those phases show the highest emission contribution at BIA.

4.8 Estimation of annual CO_2 Emission from the LTO cycle

Average fuel consumption (kg) per aircraft (according to WTC) and average CO_2 emission per aircraft (according to WTC) were calculated with available data. Table 4.17 indicates CO_2 emission per operation at BIA according to heavy and medium aircraft. With the available data of 3 months, the flight mix was calculated. BIA monthly flight schedules show slight differences in 2018[81]. Therefore, it was assumed that flight mix of BIA also has slight differences. The flight mix of BIA is 40% and 56% for heavy and medium aircraft. It was assumed that the calculated flight mix was consistent throughout the year. The aircraft mix percentage was used to estimate monthly aircraft mix. Monthly aircraft mix was multiplied with average CO_2 emission per aircraft in order to obtain monthly emission. Figure 4.33 indicates the estimated monthly CO_2 emission within the LTO cycle at BIA.

Table 4.19: CO_2 Emission per operation at BIA

	Heavy (kg)	%	Medium (kg)	%

Approach	969	19	306	19
Take-off	450	9	148	9
Climb-out	1029	20	359	22
Taxiing-in	447	9	158	10
Taxiing-out	1190	24	406	25
APU	945	19	252	15
Emission per operation	5030		1629	

According to Table 4.19, CO_2 emission per heavy aircraft at BIA is more than 3 times greater than CO_2 emission per medium aircraft. Even though the CO_2 emission from APU is disregarded from the LTO cycle, according to Table 4.19, it is 19 % from CO_2 emission per heavy aircraft and 15% from emission per medium aircraft.

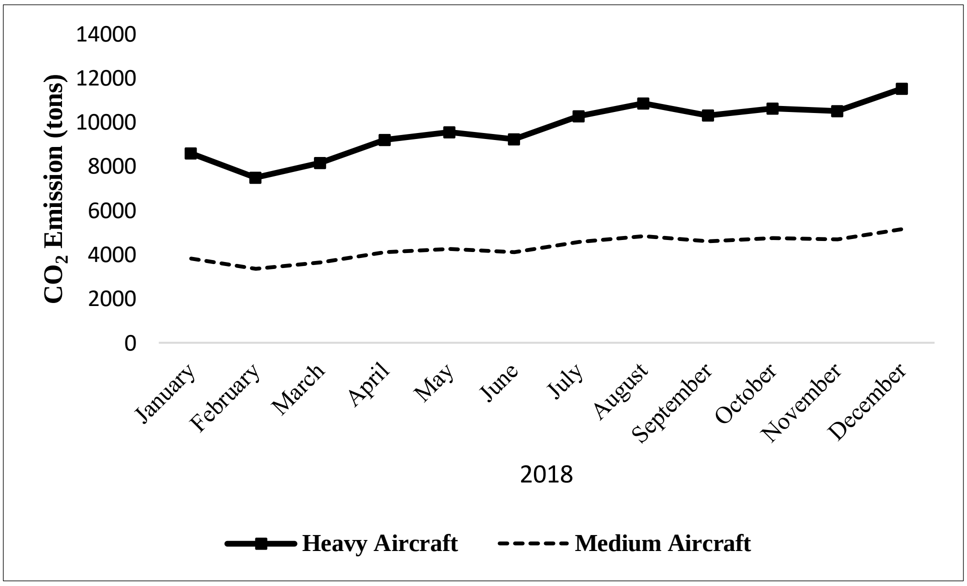


Figure 4.33: Estimated monthly CO_2 emission within the LTO cycle at BIA

4.8 Estimating CO_2 emission due to taxiing delay

4.8.1 Unimpeded Taxiing in and out time

Figure 4.34 and 4.35 show the distributions of taxiing-out time according to WTC (Heavy and medium). It is assumed that 20th percentile taxiing-out time as the unimpeded taxiing-out time according to industry practices[77]. 2 unimpeded taxiing-out times were decided according to the WTC for BIA. The 20th percentile taxiing-out time is represented in each graph and it is 9 and 8 minutes unimpeded taxiing-out time for heavy and medium aircraft at BIA. 2 unimpeded taxiing-in times were decided for arrival at BIA according to the WTC. The 20th percentile taxiing-in times are 4 and 4 minutes unimpeded taxiing-in time for heavy and medium aircraft at BIA.

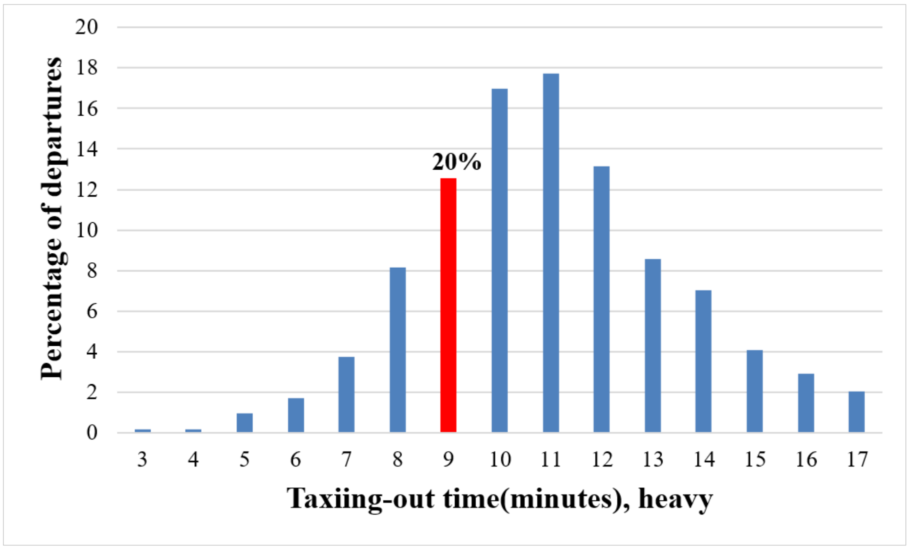


Figure 4.34: Taxiing-out time distribution of heavy aircraft

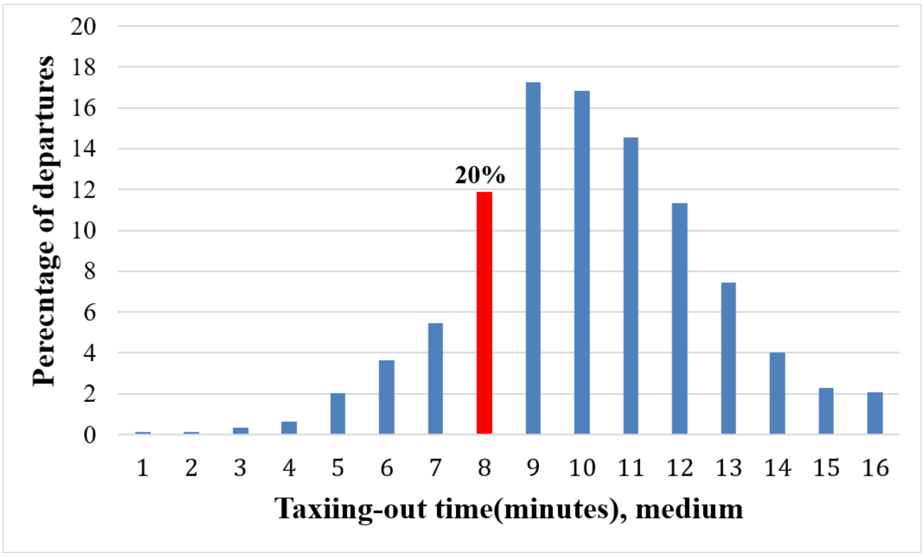


Figure 4.35: Taxiing-out time distribution of medium aircraft

4.8.3 Taxiing in and out time at the off peak

Hourly aircraft movements at BIA were observed and identified the flights at off-peak. The average taxiing in and out times of the flights at the off peak were calculated by observing the flights. Table 4.20 indicates the average taxiing time at the off peak and the unimpeded taxiing time according WTC. Then, the average taxiing time at the off peak was compared with the unimpeded taxiing time in order to justify the value of 20% from taxiing distribution as an unimpeded value. One sample t-test was used for this mean comparison and the objective of this comparison was to identify whether the average taxiing time at the off peak of BIA and the unimpeded taxiing time are significantly different from each other.

Table 4.20: Unimpeded taxiing time Vs. Off peak taxiing time

Aircraft Type		Unimpeded taxiing time(20th percentile)	Taxiing time at the off peak
Departures	Heavy	9	11
	Medium	8	9
Arrivals	Heavy	4	4
	Medium	4	4

Table 4.21: One-Sample t Test for mean comparison of off peak taxiing time and unimpeded taxiing time

						95% Confidence Interval of the Difference	
Taxi-out time	Test Value	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Heavy arrivals	4	1.83	13	0.07	0.18	-0.0157	0.3841
Medium arrivals	4	1.07	37	.31	0.5	-0.5316	1.5316
Heavy departures	11	1.49	15	.19	1.67	-1.2009	4.5343
Medium departures	9	3.2	11	0.08	1.5	0.4684	2.5316

According to Table 4.21, there were no statistically significant differences between all the sample means of heavy and medium off peak taxiing times and the unimpeded taxiing times, since all the p values are greater than 0.05(p >0.05). Therefore, the null hypothesis can be accepted. It can be concluded that the ICAO recommended unimpeded taxiing time of 20% value from the total taxiing distribution is not statistically significantly different from off peak mean taxiing time at BIA. Therefore, ICAO recommended method for calculating unimpeded taxiing time can be applied to BIA.

4.8.4 Taxiing delay

Figure 4.36 indicates the total CO_2 emission from the taxiing phase and CO_2 emission due to taxiing delay. According to the calculations of this study, emission from delay is 22% from the total CO_2 emission at the taxiing phase. This value can be increased with higher demand in the future. The taxiing time of departure is the highest contributor to delays at the taxiing phase. Therefore, the methods should be initiated to reduce taxi-out delays since it causes for CO_2 emission within the LTO cycle.

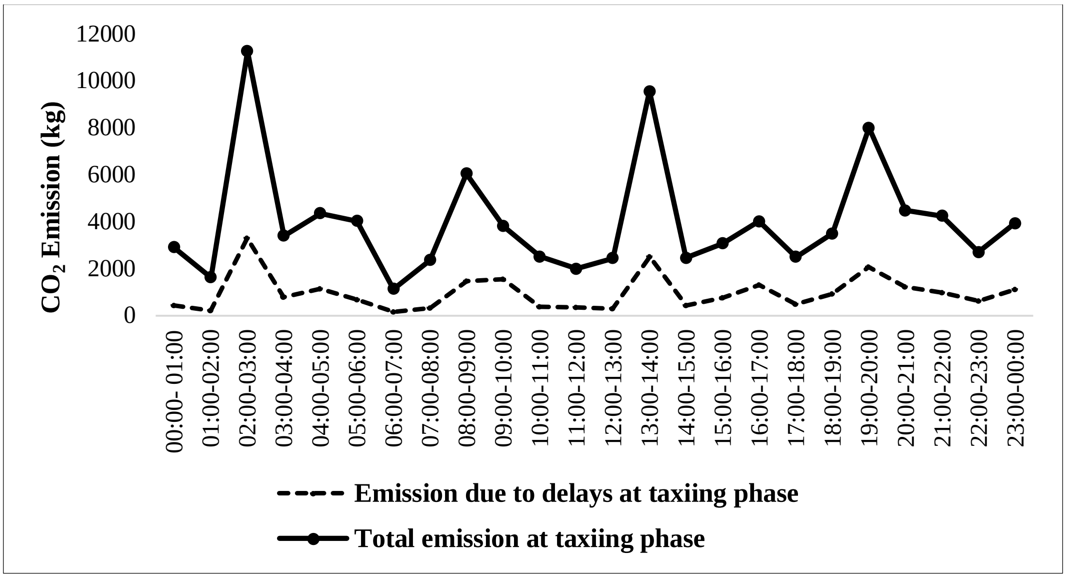


Figure 4.36: Daily total CO_2 emission and emission due to delay at taxiing phase

5. CONCLUSIONS AND RECOMMENDATIONS

All the countries are currently focusing on achieving SDGs with the support of the United Nations Development Programme (UNDP). Even though this is not a mandatory requirement member states of the UN need to take steps to achieve those goals. Emission from the LTO cycle of international flights are not required to report to any international organization. However, when achieving the SDGs every emission source is needed to evaluate to reduce its impact. Achieving the SDGs requires the partnership of all the nations to leave a better planet for future generations. Therefore, working to achieve SDGs is the responsibility of all the nations. Making climate change initiatives, implementing environmental management and sustainability programs, disclosing project effects and making future regulations are some of the reasons to maintain an emission inventory as a country.

Evaluating current emission sources is the first step to initiate emission reduction methods since it allows for setting quantitative targets for such reduction. An emission inventory can be the reference for the evaluation of work performed at reducing the GHG effect and monitoring progress over time. Policymakers need emission inventories to track trend patterns of emission and to develop policies. In general, the results of an inventory represent the information needed to identify which sources have to be controlled to reduce the emission.

5.1 Key findings

With the development of technology, more accurate methods for calculating emission are introduced over time by international organizations. However, NDCs under aviation considers only the emission from domestic flights and the emission from airport operations as the national emission of aviation sector in a country. Emissions from international flights within the LTO cycle and emission from APUs are not considered by the NDCs even those significantly influence to the local air quality.

There are limitations in current methods of evaluating emission within the LTO cycle.
Highly data intensive methods require accurate aircraft activity data which are provided by flight data recorder, electronic flight processing strips (EFPS) or proprietary software such as Aviation Environmental Design Tool (AEDT) used by FAA. Most small to medium size airports particularly in developing countries do not have access to such detail data on aircraft activities. Less data-intensive aggregate methods using broadly defined international parameters tend to overestimate or underestimate actual levels.

Current methodologies to calculate the aviation emission in the LTO cycle fails to differentiate the amount of GHG caused due to delays within different phases. Segregating delay induced GHG levels allows to initiate and justify emission reduction methods or investments. It is important to focus on the excess level of emission in order to determine effective ways of emission reduction.

Therefore, an alternative methodology is required to evaluate the emission of different phases of flight within the LTO cycle and Bandaranaike International airport (BIA) in Sri Lanka was taken as the case study for the development of the methodology. A new methodology that is more applicable to calculate CO_2 emission at BIA with available data was developed. The proposed methodology of this research can be applied to any other airport with similar conditions.

Typically, the taxiing time depends on various factors such as runway, taxiway and apron configuration, runway capacity, wind direction, weather and inefficiencies on ATC. The factors that influence to taxiing at the BIA were recognized in this study. BIA is a small airport designed with 25 runway movements per hour with 3 main aprons and flights operated to 63 destinations in 2017. According to current demand at the BIA, the parking apron does not influence the average taxiing time. Since the 3 main aprons are closely located at BIA, its influence for the average taxiing time is negligible. However, with more demand in future this location of apron also could influence for taxiing time. Currently, the day of the week does not influence the average taxiing time at BIA since the flight schedule follows the same routine throughout the year with few alterations. Since BIA situated in a tropical country, the seasonal impact for flights is not recognized.

ICAO recommends average taxiing in time and taxiing out time for international airports. By observing the actual operational data of BIA, 2 average taxiing-in times and 2 average taxiing-out time according to WTC were calculated. The actual operational values are significantly different from the ICAO values. CO_2 emission level at the taxiing-in phase of BIA will be overestimated by 52% and 45% with the ICAO recommended taxiing-in mean values for medium and heavy categories respectively. CO_2 emission level at the taxiing-out phase of BIA will be overestimated by 90% and 74% with the ICAO recommended taxiing-out mean value for medium and heavy categories respectively. Using ICAO values leads to overestimation of fuel consumption and CO_2 emission at BIA. Therefore, when estimating fuel consumption and CO_2 emission at the taxiing phase for BIA a new method for calculating emission is required. The suggested methodology provides airport specific TIM values and the results of it was compared with the actual emission using sample of operational data. When comparing the results of 2 methods for taxiing-in phase, the results of suggested method 1.6% underestimates the results of actual operation. When comparing the results of 2 methods for taxiing-out phase, the results of suggested method 3.4% underestimates the results of actual operation.

The ICAO recommended mean value for the climb-out phase is statistically significantly different from the actual operational values for both heavy and medium flights at BIA. The average climb-out durations of the heavy and medium flights are smaller than the ICAO recommended average. Therefore, the fuel consumption and CO_2 emission level of the climb-out phase at BIA will be overestimated with the use of the ICAO recommended mean value. The CO_2 emission level of the climb-out phase at BIA will be overestimated by over 100% with the use of the ICAO recommended mean value for both medium and heavy aircraft categories. When comparing the results of the suggested method and actual emission using operational data for the climb-out phase, the results of suggested method 1.5% underestimates the results of actual operation.

The ICAO recommended mean value for the approach phase is statistically significantly different from the actual operational values for both heavy and medium flights at BIA. The fuel consumption and CO_2 emission level at BIA will be underestimated at the approach phase with the ICAO recommended value. CO_2 emission from medium arrivals at the approach phase underestimates by 32% with use of ICAO recommended TIM value for the approach phase. CO_2 emission from heavy arrivals at the approach phase underestimates by 25% with use of ICAO recommended TIM value for the approach phase. When comparing the results of the suggested method and actual emission using operational data for the approach phase, the results of suggested method 4.1% overestimates the results of actual operation. Even though arrivals at BIA do not hold in the air due to congestion at the approach phase, flights at BIA show a longer period of approaching time compared to industry standards. Lack of technology which supports for approaching strategies and inefficiencies in ATC may cause for this situation.

According to the above comparison between ICAO method and the suggested method at each phases of flight with the LTO cycle, airport specific TIM values are required for more accurate CO_2 emission estimation.

The hourly emission distribution under different phases of flight within the LTO cycle at BIA indicates that the taxiing out phase contributes to the highest CO_2 emission of 33% for both heavy and medium flights. Since BIA has a single runway for both arrivals and departures, arrivals receive the priority letting the departures hold in ground. Therefore, CO_2 emission from the taxiing-in phase shows the lowest emission of 11% at BIA. According to the design of the apron at BIA, one pushback is allowed at a time within an apron and that leads idling of departures along the taxiways. In future, with more operations at BIA it can be expected more emission from the taxiing phase due to longer taxiing time. Therefore, strategies of reducing the duration of taxiing-out phase should be initiated as it causes for more emission. Even though the fuel flow rate of take-off phase is the highest compared to other phases, the flight duration at the take-off phase is the lowest compared to other phases. Therefore, the fuel consumption and the emission at the take-off phase is the lowest with 11%. With the hourly emission distribution, traffic pattern at can be recognized. This hourly emission distribution can be used to make recommendations for corrective actions related to local air quality.

Even though the CO_2 emission from the APU of an aircraft is disregarded, it is 21 % from CO_2 emission per heavy aircraft and 18% from emission per medium aircraft at BIA. Emission from the APU has a significant impact to the local air quality. Therefore, the emission from the APU is not negligible.

When deciding the unimpeded taxiing time at BIA, the ICAO recommended value of 20 percentile from the total taxiing distribution was selected. Then that value was compared with the average taxiing time at off-peak time at BIA. Those 2 values do not have a significant different from each other. Therefore, the ICAO recommended value of 20 percentile from the taxiing distribution can be used for BIA to estimate the unimpeded taxiing value. That value can be used to calculate actual taxiing delay at BIA. Current methodologies for calculating emission within the LTO cycle fails to differentiate the amount of emission caused due to delays. Operational delays in aircraft movement within the LTO cycle is one of the major contributors of excessive emission and its contribution will be increased due to higher demand in the future. Segregating delay induced CO_2 emission levels is important to initiate and justify emission reduction methods or investments.

According to the calculations of this study, currently, CO_2 emission from the delay is 22% from the total CO_2 emission at the taxiing phase. This value can be increased with higher demand in the future. The taxiing out phase of a departure flight is the highest contributor to delays within the taxiing phase and that phase should be given the most priority when initiating emission reduction methods. Most airports where a single runway is used for both arrivals and departures face the same issue of more taxiing out delays.

5.2 Limitations

Data was received for 3 months for the analysis of the taxiing phase from DAMR. When analyzing the data for climb-out and approach phases, Flightaware was used as the data source. Online survey was conducted for one week to obtain the relevant data from Flightaware. Even though Sri Lanka is a tropical country where the seasonal changes do not influence, there are some peak months, that flight operations show a slight increase. Chinese New Year celebrations in the month of December and Hajj season in the month of August are the occasions where the highest operations occur at BIA. The accuracy of emission calculation can be improved when the data is received from peak months as well. The results can be improved by further analysis to determine if TIM values very significantly across different seasons of the year. Annual emission estimation, as well as emission forecast, can be generated when monthly flight variations are identified.

Time points recorded by DAMR entries are limited to only two time points such as bay-in/out and wheels off/on. Thus, when estimating TIM values the portion of take-off run was merged with rest of the taxing phase. In the process of calculating taxiing-out time, the time spent on pushback is also included due to unavailability of data even that pushback phase does not belong to that phase. Therefore, according to the proposed methodology, taxiing-out duration is overestimating and it is still smaller than ICAO recommended value. In order to allow more precisely emission estimation at the taxiing phase, duration of pushback should be estimated. And a methodology is required to calculate the exact duration of pushback. More accurate TIM values can be estimated by differentiating components of aircraft departure procedure.

The DARM data does not contain the airborne phases of the LTO cycle. Recorded data for tracking each flight operation within the airborne phases for an extended period was not found. Thus, this study had to sample flight operations using data obtained from internet flight tracking services. ADS-B is the most common source of such data which has a high accuracy level. ADS-b data of BIA is being recorded at Airport and Aviation Services (Sri Lanka) Limited (AASL) and it contains the data of all the flights. The AASL stores the ADS-b data for a short period due to their limited storing capacity. If there is a process to store and obtain the data from ADS-b at the AASL, more accurate TIM values under different phases of flight can be estimated. In this study, FlightAware is used obtain the data from airborne phase within the LTO cycle.

Even though the FlightAware issues data using ADS-b, obtaining data from FlightAware is expensive and all the flights are not tracked especially the light aircraft.

Fuel usage of APU at BIA was unable to estimate accurately due to the unavailability of recorded data in related to APU usage. Therefore, the fuel consumption and CO_2 emission of APU was estimated using the industry practices and those values may be over or underestimate the actual operation. Due to the taxiway congestion, aircraft have to wait at the gate for departure clearance from ATC. Due to inefficiencies at the gate operation, aircraft have to wait at the gate. Then the APU operates with consuming additional fuel at this stage. A methodology can be developed to estimate actual fuel consumption of APU.

5.3 Recommendation

There are many factors that affect the time spent on taxiing time. Wind direction, time of day, distance from the gate to the runway, weather (de-icing needed or low visibility), congestion levels (length of the queue to take-off), apron/taxiway layout and aircraft type (wake vortex) are some of the factors that decide the taxiing time. In this research, the distance from the gate to the runway, the day of the week and the type of aircraft were the only factors considered according to the availability of data. All other factors can also be considered in future research to obtain a more accurate estimation of taxiing time.

ICAO recommended TIM values are based on default ICAO LTO cycle engine thrust settings. However, the default engine thrust indicates the maximum thrust levels under a specific phase and this is one of the reasons for overestimating emission levels. The fuel flow rate of the engine differs according to the engine thrust level and pilots do some changes of engine thrust under different phases of flight in order to save fuel. Therefore, for more precisely emission estimation, the actual engine thrust levels should be identified at specific stages.

Hourly emission distribution can be used for a future study of traffic pattern at BIA and its influence for the local air quality. The corrective actions can be obtained using that study in order to improve the local air quality.

Delays at the taxiing phase was identified in this research. The method can be developed to identify the delays at the other phases of flight as well. Then necessary steps can be taken to reduce delays, and consequently, CO_2 emissions will be reduced. With more demand in the future, it can be expected more aircraft operations and more delays. Arrivals may stack due to runway congestion and that causes for additional fuel consumption and more CO_2 emission. Therefore, focusing on the delays at the other phases of flight will be essential in future.

Some aircraft use Ground Power Units (GPUs) as an alternative to APU. Then the fuel consumption of GPU is also needed to consider as an emission source within the LTO cycle. In this study the CO_2 emission from GPU was not included due to unavailability of data. A method should be developed to obtain data to calculate GPU operational time.

The usefulness of accurate TIM calculations is very important for airlines, because the knowledge of the duration of the aircraft maneuvers at the airport gives arguments in negotiations with the air traffic control for their fuel optimization. Airlines are keen to save the fuel since it carries a huge cost for them. Airlines strive to save fuel, and consequently, CO_2 emissions will be reduced.

The approach can be adopted by other agencies facing a similar scenario concerning limited data availability and different operating characteristics to make an accurate estimate of the emission levels. Thus, the outcomes encourage stakeholders to initiate emission reduction methods. Specific stages where emission occurs should be identified separately to improve emission reduction strategies. Green practices improve the international image of the airport. Thus, by maintaining an emission inventory, an airport can obtain more economic and environmental benefits.

6. REFERENCES

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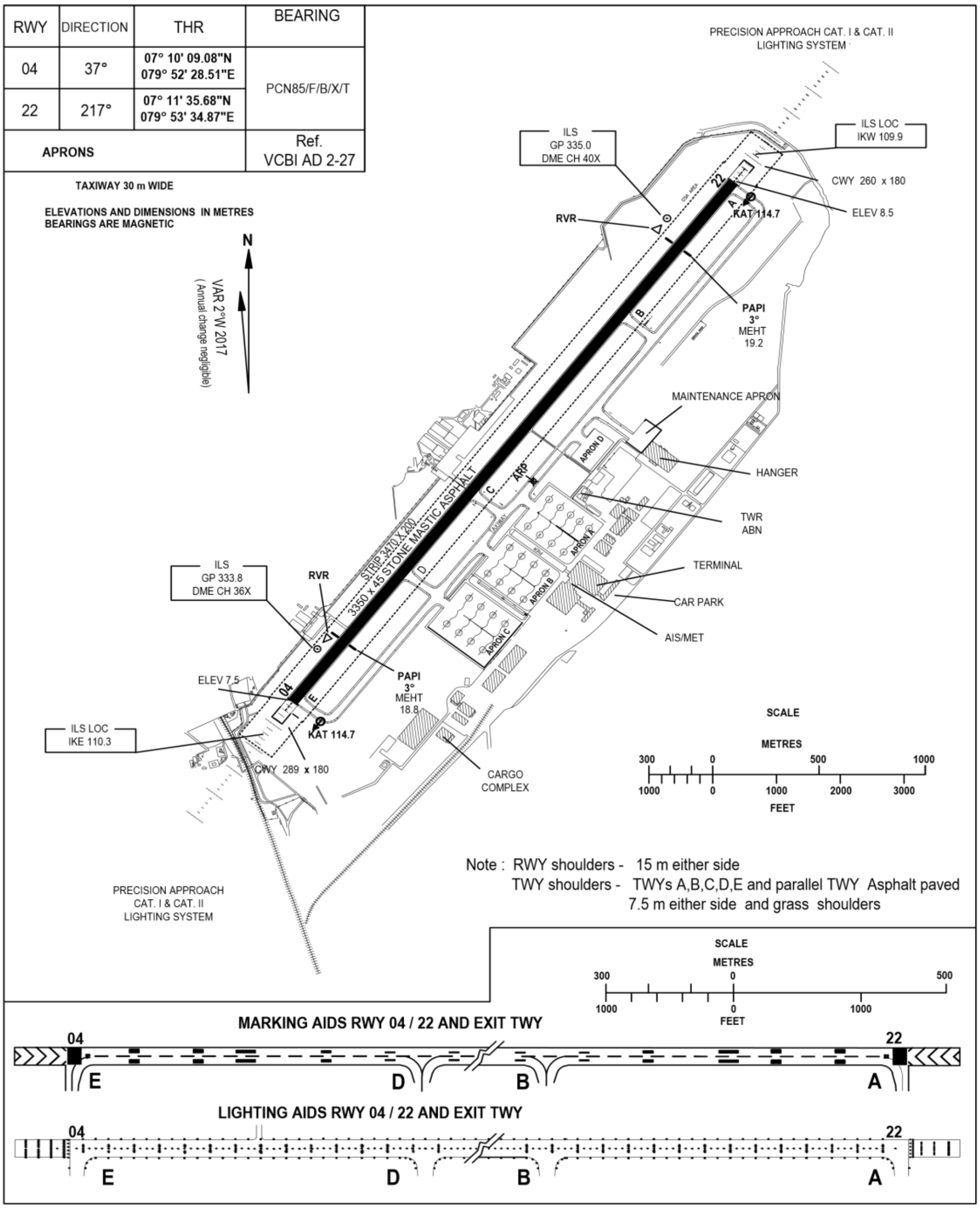
Appendix- A: Layout of BIA



RWY	DIRECTION	THR	BEARING
04	37°	07° 10' 09.08"N 079° 52' 28.51"E	PCN85/F/B/X/T
22	217°	07° 11' 35.68"N 079° 53' 34.87"E	
APRONS			Ref. VCBI AD 2-27

TAXIWAY 30 m WIDE

ELEVATIONS AND DIMENSIONS IN METRES
BEARINGS ARE MAGNETIC

Note : RWY shoulders - 15 m either side
TWY shoulders - TWYs A,B,C,D,E and parallel TWY Asphalt paved 7.5 m either side and grass shoulders