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# Evaluation of Carbon Emission During Taxi-Out at Tribhuvan International Airport: A Case Study of Nepal Airlines Corporation

**by**

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**A THESIS**

**SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING IN PARTIAL FULLFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE IN RENEWABLE ENERGY ENGINEERING**

**DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING**

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# ABSTRACT

Aircraft ground operations largely contribute to carbon dioxide emissions, particularly during taxi-out operations, where prolonged engine idle conditions increase fuel burn. This study evaluates the relationship between $CO_2$ emissions and taxi-out time along with flight frequency associated for Airbus A320 and A330 fleets being operated by Nepal Airlines Corporation. The monthly and annual operational data obtained from the airlines were analyzed that helped in identifying departure trends, taxi-out duration, and carbon dioxide emission patterns.

The results demonstrate that aircraft A320 has higher mean taxi-out time while aircraft A330 has higher $CO_2$ emissions, reaching up to 3.18 tons per flight compared to 1.18 tons for A320 per flight. The peak emissions were observed in 2023 for A330 (2167.78 tons) and 2022 for A320 (1331.92 tons) due to higher traffic intensity. A strong proportional relationship between taxi-out time and emissions was identified that was supported by statistical validation using multiple linear regression model ($R^2 > 0.99$). Single-engine taxiing scenario analysis shows substantial fuel and cost savings potential. By 2030, fuel savings are projected to reach approximately 1080 tons for A330 and 197.89 tons for A320, with corresponding economic benefits of up to NPR 170 million and NPR 32 million respectively. The adaptation of electric tow technologies during taxi-out operations reduces the $CO_2$ emissions by 90% for A330 and 83% for A320. The annual energy expenditure reduces by NPR 7.53 million along with a cost benefit ratio of 0.65 and a payback period of 9.41 years.

This study concludes that taxi-out operations can be optimized through improvement in traffic management. The adoption of fuel-saving methods can reduce emissions and operational costs. These findings support a practical pathway to integrate taxi-out emission mitigation into airport sustainability policies and carbon management frameworks.

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| | |
|---|---|
| AFL | Aircraft Flight Log |
| ANOVA | Analysis of Variance |
| ATC | Air Traffic Control |
| BCR | Benefit-Cost Ratio |
| CAAN | Civil Aviation Authority of Nepal |
| $CO_2$ | Carbon Dioxide |
| EGTS | Electric Green Taxiing System |
| ETV | Electric Towing Vehicle |
| FAA | Federal Aviation Administration |
| FDR | Flight Data Recorder |
| GHG | Green House Gas |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| Kwh | Kilowatt Hour |
| LTO | Landing and Take-Off |
| MLR | Multi Linear Regression |
| NAC | Nepal Airlines Corporation |
| QAR | Quick Access Recorder |
| SET | Single Engine Taxiing |
| TIA | Tribhuvan International Airport |
| WAM | With Additional Measures |
| WEM | With existing Measures |

# CHAPTER ONE: INTRODUCTION

## 1.1 Background

The aviation industry plays an important role in economic growth, international trade, tourism, and global connectivity. Over the past few decades, the demand of air transport has increased rapidly due to population mobility, globalization and airlines network expansion. Despite the economic benefits, aviation contributes to greenhouse gas (GHG) emissions, particularly carbon dioxide ($CO_2$), which is a major driver of climate change. The aviation sector contribute to annual 2.4% of global $CO_2$ emissions (Graver, 2019). Aircraft emissions occur during all phases of flight, from ground operations to cruise at high altitude. While considerable attention is often given to emissions during cruise flight due to its long duration, ground operations, especially taxi-out - also represent a meaningful source of fuel consumption and carbon emissions. At congested airports, prolonged taxi times can significantly increase total fuel burn per flight.

Tribhuvan International Airport (TIA), located at Kathmandu, is Nepal's largest the busiest airport, serving as the country's primary gateway for international and domestic flights. Built in 1955, TIA has seen exponential growth in air traffic over the decades, but its infrastructure has struggled to keep pace with this growth. The airport operates with a single runway that is 3,050 meters (10,007 feet) long which handles both takeoff and landing operations for all aircrafts. This single runway system is coupled with limited taxiway space that often leads to congestion, especially when multiple aircrafts are arriving and departing and during peak hours. Taxi-out refers to the movement of an aircraft starting from parking stand to the runway holding point prior to the takeoff where the aircraft engines operate at idle or near-idle thrust. Although the thrust setting is low, continuous fuel combustion during this phase results in steady carbon emissions which when multiplied across thousands number of flights operating annually. Even small increase in taxi time can produce substantial cumulative environmental and economic impacts. Hence, evaluating carbon emissions during taxi-out operations at Tribhuvan International Airport is essential to improve operational efficiency, reduce environmental impact, and to support sustainable aviation development in Nepal.

Aviation is a rapidly growing sector contributing significantly to global greenhouse gas emissions, particularly carbon dioxide ($CO_2$). As global concerns about climate change intensify, the aviation industry is under pressure to reduce its carbon footprint. The

International Civil Aviation Organization (ICAO) reports that airport ground operations, including aircraft taxiing, significantly contribute to overall emissions.

### 1.1.1 Phases of flight

Aircraft operations can be divided into distinct phases of flight, each characterized by different engine power settings and fuel consumption rates. Understanding these phases is important for identifying where emissions occur and which phases offer potential for reduction. The major phases of flight include:

1. Parking Phase: In this phase the aircraft is at the gate where auxiliary power units may operate.
2. Taxi Phase: This phase includes taxi-out phase (departure phase) and taxi-in phase (after landing).
3. Takeoff Phase: This phase requires high thrust for runway acceleration.
4. Climb Phase: This phase also increases thrust rapidly until cruise altitude.
5. Cruise Phase: This phase is defined as a long-duration flight at higher altitude.
6. Descent Phase: In this phase, the engine thrust is reduced.
7. Approach Phase: This phase includes the alignment and preparation for landing.
8. Landing and taxi-in Phase: This phase includes the ground roll and taxing the aircraft to gate.

For airport-level emission studies, the International Civil Aviation Organization (ICAO) defines the Landing and Take-Off (LTO) cycle, which includes all operations below 3,000 feet above ground level:

- Taxi/Idle
- Takeoff
- Climb-out
- Approach

Among these phases, taxi operations are particularly significant for local air quality because emissions occur directly at ground level near airport surroundings. Although cruise phase is the largest consumer of the fuel due to its long duration during aircraft operation, taxi-out emissions are operationally important because they are:

- Influenced by airport congestion

- Directly related to ground movement efficiency
- Operational improvements can potentially reduce the emissions
- Highly associated with avoidable fuel burn

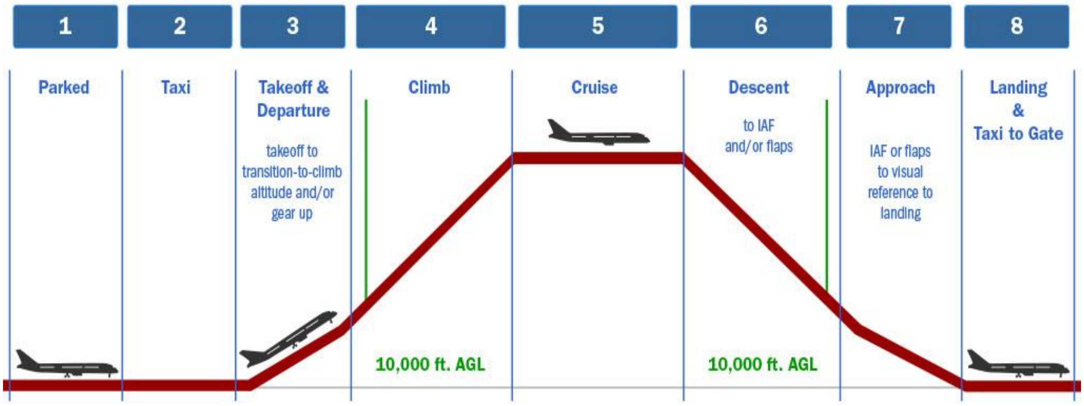

Figure 1.1: Phases of flight

Therefore, this study focuses specifically on evaluating carbon emissions generated during the taxi-out phase.

### 1.1.2 Operational characteristics and airport layout

Tribhuvan International Airport is located at an elevation of 1,338 meters above sea level in Kathmandu Valley. This airport operates under significant geographical and infrastructural constraints as it is surrounded by mountainous terrain and has rapid urban development.

#### Runway system

The airport operates using a single runway (02/20) which is 3,050 meters long. This runway facilitates both arrivals and departures flights. The absence of a parallel secondary runway requires careful sequencing of aircraft movements, sometimes leading to departure queues.

#### Taxiway system

The taxiway configuration includes:

- Connecting taxiways between aprons and runway
- Partial parallel taxiway segments
- Holding points near runway thresholds
- Limited bypass and overtaking capability

Because there is no full-length parallel taxiway along the entire runway, aircraft may need to wait for runway clearance before proceeding, increasing taxi duration.

**Apron and terminal layout**

The airport consists of:

- International apron area near the international terminal
- Domestic apron area serving domestic airlines
- Multiple aircraft parking stands

Aircraft parked at different stands travel varying taxi distances to reach the runway holding point. This variation creates differences in taxi-out time.

### 1.1.3 Types of aircraft and passenger volume

Tribhuvan International Airport handles a significant volume of air traffic annually. The airport has managed around 7-8 million passengers annually along with more than 100,000 aircraft movements inside the airport. The traffic demand increases rapidly during major national festivals and peak tourism seasons, particularly autumn (September-November) and spring (March-April). During these peak seasons, congestion occurs both on taxiways and at runway holding points frequently. Mixed traffic operations including domestic turboprop aircraft, narrow-body international jets, and occasional wide-body aircraft further increase the complexity in ground movement operations. The types of aircrafts operating in TIA is represented in Table 1.1.

Table 1.1: Aircrafts operating in TIA

| Category | Aircraft Type | Aircraft Model |
|---|---|---|
| Domestic Airlines | Turboprop | ATR 42 |
| | Turboprop | ATR 72 |
| | Turboprop | De Havilland Canada DHC-8 (Dash 8 Q400) |
| | STOL Aircraft | De Havilland Canada DHC-6 Twin Otter |
| | Helicopter | Airbus H125 / AS350 |
| | Helicopter | Bell 206 |
| | Helicopter | Mil Mi-17 |
| | Narrow-body Jet | Airbus A320 |

| Category | Aircraft Type | Aircraft Model |
|---|---|---|
| International Airlines | Narrow-body Jet | Airbus A321 |
|  | Narrow-body Jet | Boeing 737 (NG / MAX) |
|  | Wide-body Jet | Airbus A330 |
|  | Wide-body Jet | Boeing 777 |
|  | Wide-body Jet | Boeing 787 Dreamliner |
|  | Cargo Aircraft | Ilyushin Il-76 (occasional) |

### 1.1.4 Relationship between taxi-out emissions and airport layout

The airport's growing traffic demand, single-runway configuration and limited taxiway flexibility has direct influence on taxi-out duration. The taxi-out time includes pushback and engine start, aircraft movement to runway, queuing for departure and takeoff clearance. The aircrafts engine operates at idle during taxi phases where fuel consumption and taxi time are directly proportional to each other. Hence, reducing taxi-out duration, even by 2 to 4 minutes per flight can have higher impact in fuel savings and carbon emission reduction. Taxing process contributes up to 20 % of the emissions of the overall flight (Camilleri & Batra, 2021). Although there are infrastructure constraints at Tribhuvan International Airport, improving taxiing process helps to provide a practical and achievable strategy to reduce aviation-related carbon emissions in Nepal.

## 1.2 Statement of problem

The challenges of limited runway infrastructure and growing air traffic have led to increased taxiing times and increased carbon dioxide emissions at Tribhuvan International Airport. This extended taxi time has resulted in higher fuel consumption and elevated levels of carbon dioxide ($CO_2$) emissions, worsening the airport's environmental footprint.

Currently, there are insufficient data and fewer studies have been done regarding emissions generated during taxing operations at TIA. Similarly, the exploration of emission mitigation strategies is limited due to fewer studies performed in this field. Without a clear understanding of the emissions during taxing phase and exploring the potential for emission reduction, the airport is at risk of continued inefficiencies and increased environmental impact as air traffic keeps growing.

## 1.3 Objectives

### 1.3.1 Main objective

The main objective of this study is to evaluate current $CO_2$ emission levels during taxi-out operation at TIA and explore mitigation strategies to reduce the emissions.

### 1.3.2 Specific objectives

The specific objectives of this study are:

- To quantify the carbon emissions generated during taxi-out operation at TIA
- To project the $CO_2$ level emissions generated by the aircrafts till 2030
- To propose mitigation strategies for reducing taxiing-related carbon emissions at TIA

## 1.4 Limitations of the study

Despite the use of real operational taxi-in and taxi-out time data, this study is subject to several limitations primarily related to data availability and modeling assumptions.

- Engine idle fuel flow rates were obtained from the ICAO Aircraft Engine Emissions Databank rather than actual engine fuel flow values recorded in the Flight Data Recorder (FDR) or Quick Access Recorder (QAR). This approach was adopted due to the unavailability of detailed engine performance data from airline operational records
- The total taxi-out time was treated as a single continuous operational phase without distinguishing between different sub-phases such as initial pushback and engine start, straight-line taxi, turning maneuvers, stop-and-go queueing, acceleration after holding points

# CHAPTER TWO: LITERATURE REVIEW

According to fourth assessment report (IPCC AR4) “Total $CO_2$ aviation emissions is approximately 2 % of the Global Greenhouse Emissions. The amount of $CO_2$ emissions from aviation is expected to grow around 3-4 per cent per year; and Medium-term mitigation for $CO_2$ emissions from the aviation sector can potentially come from improved fuel efficiency. The Study highlights medium-term mitigation for $CO_2$ emissions from the aviation sector can potentially come from improved fuel efficiency. However, such improvements are expected to offset the growth of $CO_2$ aviation emissions only partially.

Nepal has committed to achieving net-zero greenhouse gas emissions by 2045, with the aim to reduce carbon emissions across all sectors, including aviation. The aviation sector is a significant contributor to global carbon emissions, and many countries, including Nepal, are developing strategic actions to mitigate these impacts. The report “Nepal’s long-term strategy for Net-zero emission” has established strategic action such as switching to synthetic fuels/biofuels in aviation. It has specific milestones to track progress in reducing transport emissions such as 1.9 mMtCO2e reduction in 2030 and 8.2 mMtCO2e reduction in 2050, i.e., 26 % and 41% reduction in 2030 and 2050 respectively compared to the REF scenario by WEM approach and 2.1 mMtCO2e emission reduction in 2030 and 19.5 mMtCO2e in 2050, i.e.,30 % and 97 % reduction in 2030 and 2050 respectively compared to the REF scenario by WAM approach (MoFE, 2021).

In research study “Evaluation and mitigation analysis of carbon footprint for an airline operator: Case of Nepal Airlines Corporation” (Tuladhar et al., 2021,), has conducted evaluation of emission carbon footprint by overall operation by an airline operator NAC. Carbon footprint in terms of Carbon Dioxide ($CO_2$) emission has been calculated for NAC’s airline operations per individual aircraft, fleet-type, and operating sector, and total ground handling operations. In each of the study years, contribution to NAC’s total $CO_2$ production from its domestic fleet was found out to be exceedingly small (below 6% of yearly total), even though its fleet number outnumbered that of the international fleet. The study has suggested Reductions in fuel on-board as per prescribed levels, better airport slot management and selection of long-haul flight destinations have been identified as potential mitigation strategies for $CO_2$ emission from international sector (Tuladhar et al., 2021).

Nikoleris et al. explored how taxi times affect overall fuel burn and emissions at U.S. airports. The study identifies congestion, inefficient ground operations, and limited runway availability as key contributors to extended taxiing times. The findings suggest that improving ground traffic flow and optimizing runway use can reduce emissions (Nikoleris et al., 2011).

A report by IATA (2020) highlights the benefits of electric taxiing systems, where aircraft can be towed by electric-powered vehicles during taxiing, eliminating the need for engine use and reducing emissions. The research focuses on a system for ground maneuvering of aircraft called Taxibot where the principles, advantages, and disadvantages of the Taxibot system with basic estimations about economic benefits of the system were studies. The Taxibot system is an available option for cost reduction (Hospodka, 2014). Airports such as Schiphol have already implemented these systems with success.

Zhan et al. performed a study based on the aircraft's taxiing motion model. This study discretized the taxiing speed and adopted a multitarget immune optimization method to study the specific relationship between taxiing speed and fuel consumption when an aircraft is launched using a fixed path relationship. This study provides a methodology for estimating emissions and evaluating different scenarios for emission reduction (Zhan et al., 2017).

FAA has stated net carbon emission reductions by 2050, and IATA has set net reductions in 2050 by 50% (taking 2005 as base year). Also, there are requirements established by Civil Aviation Authority of Nepal (CAAN) applicable to an airplane operator that produces annual $CO_2$ emissions greater than 10,000 tons from the use of an airplane with Maximum Take-off mass greater than 5,700 kg (about 12566.33 lb) conducting international flights on or after 1st January 2019.

Studies have shown that taxiing emissions represent a huge portion of total airport-related emissions. Airports globally are adopting strategies like electric taxiing and optimizing ground traffic management to reduce their carbon footprint. For example, Amsterdam’s Schiphol Airport has introduced electric tugs for aircraft taxiing, significantly reducing $CO_2$ emissions. However, limited studies have been conducted in the context of developing countries like Nepal, where airport infrastructure and technology differ. This study aims to fill that gap by providing an empirical evaluation of taxiing emissions at TIA. Various other studies done regarding carbon taxiing are illustrated in Table 2.1.

Table 2.1: Comparison of different research and their findings

| Article, Author, Journal, Year | Major findings | Methodology implemented | Research gap |
|---|---|---|---|
| Towards Sustainable Airport Operations: Emission Analysis of Taxiing Solutions (Maciejewska & Kurzawska-Pietrowicz, *Sustainability*, 2025) | • Aircraft taxiing is a major contributor to airport-area emissions during the LTO cycle.<br>• Electric towing vehicles (ETVs) reduce CO and NOx emissions to nearly zero.<br>• $CO_2$ emissions with ETVs are drastically lower (2.8-4.4 kg) compared to full-engine taxiing (380–450 kg).<br>• Single-engine taxiing halves emissions | • Comparative emission analysis of taxiing methods: full-engine, single-engine, electric, diesel, and petrol towing.<br>• Use of ICAO LTO cycle emission indices for aircraft engines.<br>• Calculation of ETV emissions based on electricity generation emission | • Full life-cycle assessment (LCA) of electric towing vehicles (battery production, recycling) is only partially addressed.<br>• Real-world taxiing conditions (stop-and-go, congestion, turning delays) are simplified.<br>• Airport-specific charging infrastructure, fleet size optimization, |

| Article, Author, Journal, Year | Major findings | Methodology implemented | Research gap |
|---|---|---|---|
| | compared to full-engine taxiing.<br>- Petrol-powered towing vehicles can emit more CO than full-engine taxiing.<br>- Emissions are expected to increase by 30% (Poznań) and 71% (Warsaw) by 2040 without intervention. | factors in Poland.<br>- Case studies at Warsaw Chopin (EPWA) and Poznań (EPPO) airports using real taxi times.<br>- Regression-based air traffic forecasting to predict long-term emission trends up to 2040. | and operational constraints need deeper analysis.<br>- Integration of renewable electricity scenarios and uncertainty analysis requires further research. |
| Optimization of Aircraft Taxiing Strategies to Reduce the Impacts of Landing and Take-Off Cycle at Airports (Di Mascio et al., | - Taxiing phases contribute significantly to local airport emissions, especially HC and CO.<br>- Single-engine taxiing (SET) provides immediate emission and | - Advanced ICAO Airport Air Quality Manual methodology for emission inventory.<br>- Use of real operational taxiing time data from a | - Results are based on one case-study airport, limiting generalization.<br>- Life-cycle environmental impacts of onboard systems and electric towing |

| Article, Author, Journal, Year | Major findings | Methodology implemented | Research gap |
|---|---|---|---|
| *Sustainability*, 2022) | fuel reductions with no infrastructure cost.<br>• Reducing taxiing time through better surface traffic management yields substantial emission reductions.<br>• Onboard electric taxiing systems (MES) achieve large reductions in fuel consumption and pollutants during taxi-out.<br>• Best short-term solution: SET.<br>• Best long-term solution: combination of reduced taxi-in time and | medium-size Italian airport.<br>• Application of Boeing Fuel Flow Method 2 (BFFM2) to account for real atmospheric conditions.<br>• Comparative scenario analysis of four taxiing strategies: SET, dispatch towing, onboard systems, and reduced taxi time.<br>• Cost–benefit analysis of fuel consumption for each scenario. | (battery production, disposal) are not assessed.<br>• Operational constraints such as pilot acceptance, ATC workload, and safety risks need further investigation.<br>• Interaction with other airport emission sources (road traffic, ground support equipment) is not fully integrated.<br>• Future impacts of renewable electricity use and emerging propulsion technologies |

| Article, Author, Journal, Year | Major findings | Methodology implemented | Research gap |
|---|---|---|---|
| | onboard systems. | | require further study. |
| Detailed estimation of fuel consumption and emissions during aircraft taxi operations at airports (Nikoleris et al., 2011) | • Taxi operations contribute a significant portion of total LTO fuel burn and emissions, especially at congested airports.<br>• Real taxi times are often much longer than ICAO standard times → leading to underestimation of emissions in inventories.<br>• Taxi-out fuel burns increase significantly with congestion and queuing delay.<br>• Demonstrated large potential emission reductions | • Used real operational surface data from a major U.S. airport (ASPM database).<br>• Developed a data-driven estimation model for taxi fuel burn.<br>• Classified aircraft by type and engine characteristics.<br>• Applied fuel flow rates at idle thrust for taxi phase.<br>• Compared real taxi times with ICAO standard LTO assumptions.<br>• Performed statistical | • Traditional emission inventories rely on fixed ICAO taxi time assumptions, which underestimate real-world emissions.<br>• Lack of high-resolution operational data in earlier studies. Limited understanding of congestion impact on taxi emissions.<br>• Need for improved surface management strategies based on realistic |

| Article, Author, Journal, Year | Major findings | Methodology implemented | Research gap |
|---|---|---|---|
| | through improved surface management (reduced taxi time).<br>- Emission estimates based on real operational data are substantially higher than standard inventory models. | analysis on taxi-out and taxi-in distributions.<br>- Calculated fuel burn and emissions using time × fuel flow approach. | emission models. |

# CHAPTER THREE:  METHODOLOGY

The systematic approach implemented for this study is outlined in this section. The research will employ a combination of data collection, analysis, emission and impact comparison. The overall methodology adapted in this study is indicated in Figure 3.1.

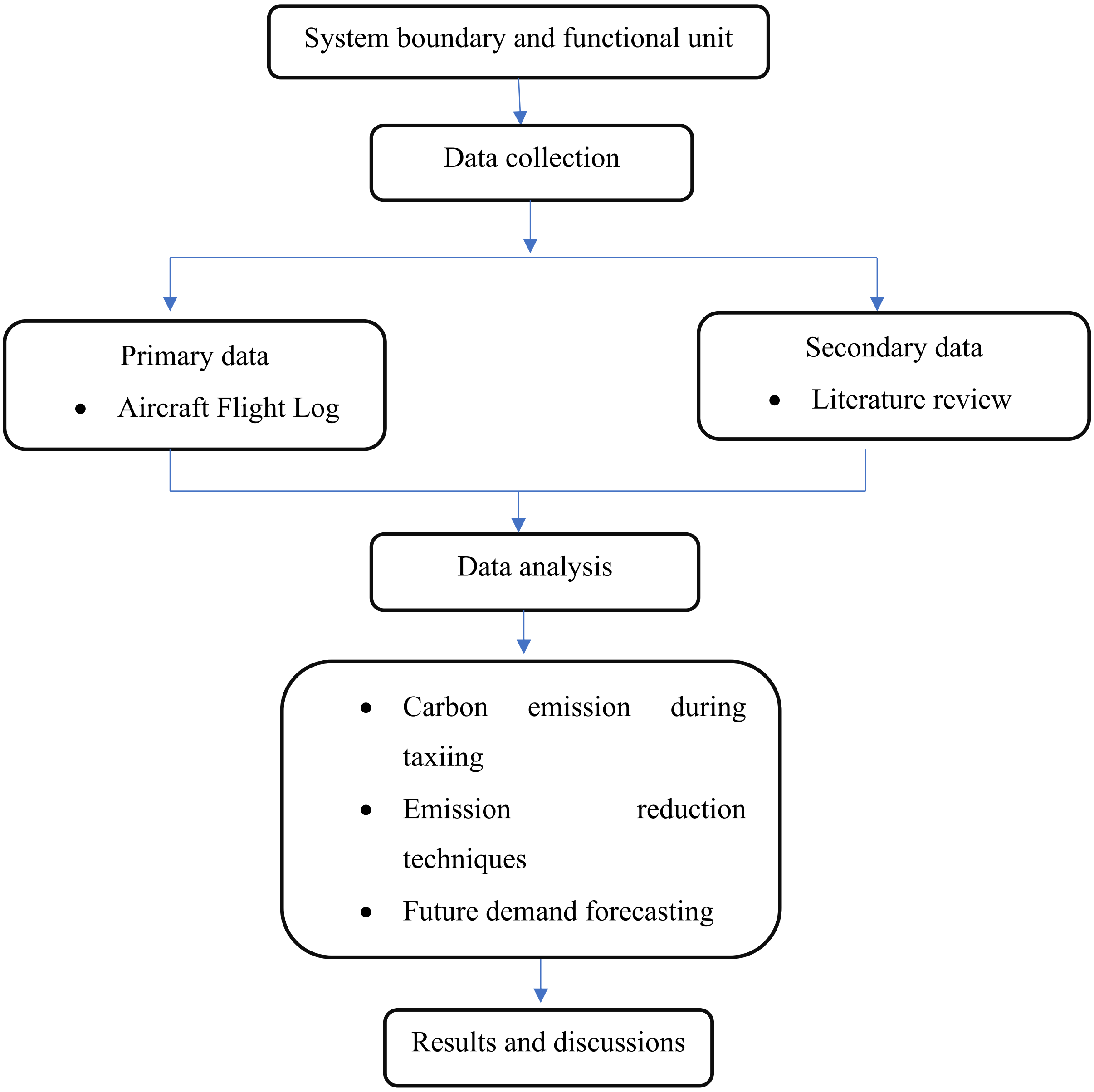

Figure 3.1: Methodological flowchart

The methodological framework consists of: (i) system boundary definition, (ii) taxi-out segmentation, (iii) data collection, (iv) emission calculation (v) scenario analysis, and (vi) sensitivity and economic assessment.

### 3.1 System boundary and functional unit

The system boundary is limited to the taxi-out phase of the take-off cycle. Processes included are pushback, engine start and warm-up, taxi-out, and holding at the runway threshold. Cruise, climb, descent, and terminal building emissions are excluded to maintain an analytical focus on ground-level emissions. The functional unit is defined as Tonnes of $CO_2$ emitted per departure from Airbus A330 and A320 in TIA being operated by Nepal Airlines Corporation.

### 3.2 Data collection

The data collection was performed to determine the aircraft-specific parameters for airbus A330 and A320. The different parameters used for the types of aircrafts studied are represented in Table 3.1.

Table 3.1: Parameters for the aircrafts

| Parameter | A330 | A320 |
|---|---|---|
| Engine type | V2527E-A5 | RB211TRENT772B-60 |
| Idle fuel flow rate (kg/s) | 0.27 | 0.128 |
| Taxi thrust setting (%) | 7 | 7 |

These parameters are obtained from:

- ICAO Engine Emissions Databank
- Aircraft manufacturer technical documentation

### 3.3 Emission Calculation Model

The carbon dioxide emission (E) during taxi-out operation in the given taxi-out period $T_i$ is calculated using equation (3.1).

$$E = T_i \times f_i \times N_i \times E_{ik} \tag{3.1}$$

where $E_{ik}$ is the $CO_2$ emission factor (3.16 kg $CO_2$/kg fuel), $N_i$ is the number of engines on the aircraft and $f_i$ is the fuel flow rate at idle (Zhang et al., 2019).

### 3.4 Scenario development

To evaluate potential mitigation strategies for reducing taxiing-related emissions at Tribhuvan International Airport (TIA), three operational scenarios were developed and compared with the existing baseline taxiing practice. Scenario analysis is widely used in aviation emission studies to assess the environmental benefits of alternative operational strategies without requiring real-world implementation (Zhang et al., 2019). These scenarios simulate different taxiing modes and estimate their potential impact on fuel consumption and carbon dioxide ($CO_2$) emissions.

#### 3.4.1 Baseline taxi operation

The baseline scenario represents the current operational practice at TIA, where aircraft taxiing using both engines operating at idle thrust during the taxi-out phase. In this mode, aircraft engines remain active throughout taxi-out until take-off clearance is granted. Fuel consumption and emissions under this scenario are calculated using taxi time, fuel flow rate, and emission factors derived from the ICAO Landing and Take-Off (LTO) cycle methodology.

This scenario is considered as a reference condition in this study against which the alternative mitigation strategies are compared. Previous studies shows that dual-engine taxiing provides more contribution towards airport surface emissions as both the engines continue to burn fuel even at idle thrust during extended taxi delays (Zhang et al., 2019). Hence emission calculation under baseline conditions is essential for evaluating the effectiveness of emission-reduction strategies.

#### 3.4.2 Single engine taxi-out operation

This scenario evaluates the potential emission reduction using Single Engine Taxing (SET) operations. In this strategy, aircraft taxi using only one engine while the other engine remains shut down until just before take-off. This operational procedure reduces fuel consumption and associated emissions because fewer engines are operating during taxiing. Single-engine taxiing has been widely promoted as an operational measure to reduce ground-level emissions and fuel burn in the aviation sector. Studies have shown that SET can significantly reduce fuel consumption and pollutant emissions during taxi operations by limiting engine usage (Stettler et al., 2018). The fuel consumption during single engine taxiing may decrease by approximately 21.1% in case of airbus A320 (Stettler et al., 2018). Similarly, $CO_2$ emission reduces by 33.39% in airbus A330 while single engine taxiing is implemented while compared to dual engine taxiing (Cao et al., 2023).

For this scenario, the emission calculation is modified by considering the fuel flow rate of only one operating engine during taxi-out, while maintaining the same taxi time obtained from the baseline dataset. The resulting emissions are then compared with baseline values to estimate the potential reduction achievable through SET operations at TIA.

### 3.4.3 Electric tow vehicles operation

The third scenario evaluates the implementation of electric tow vehicle operation in taxing operation. Electric tow vehicle operation is considered as an advanced ground handling strategy where all the engines of the aircraft remain switched off during taxiing, and the aircraft is moved by an external electric towing vehicle from the gate to the runway holding point. Electric taxi systems and towing technologies have been proposed as effective solutions for reducing airport surface emissions because they eliminate the need for aircraft engine operation during taxiing. Research shows that replacing conventional taxiing with electric towing systems can significantly reduce fuel consumption and associated carbon emissions during ground operations (Stockford et al., 2019). In this study, the emissions under this scenario are estimated by assuming zero aircraft engine fuel consumption during taxiing, while accounting for minimal auxiliary power usage.

The following assumptions are considered for the implementation of electric tow vehicle operation:

- Aircraft engines are switched off throughout the taxi-out phase.
- Taxiing is performed using an electric tow vehicle connected to the aircraft nose gear.
- Taxi-out time remains equal to the baseline scenario.
- No onboard fuel consumption occurs during taxiing.

- Electrical energy consumption depends on the tractor power rating and operating duration.
- The emission factor of electricity is based on the national grid characteristics, which in the case of Nepal is predominantly hydropower-based.

The total electrical energy required for towing operations is calculated based on the number of flight movements, average taxi-out time, and power rating of the electric tractor as represented in equation (3.2).

$$E_{elec} = N_f \times T_{taxi} \times P_{tractor} \tag{3.2}$$

where $E_{elec}$= total electrical energy consumption (kWh/year), $N_f$= number of flights per year, $T_{taxi}$= average taxi-out time (hours), $P_{tractor}$= power rating of the electric towbarless tractor (kW)

The carbon emissions that are associated with electric towbar-less operation are indirect emissions that occur due to electricity generation from hydropower. The emissions are calculated using the grid emission factor as represented in equation (3.3).

$$E_{ETT} = E_{elec} \times EF_{grid} \tag{3.3}$$

where $E_{ETT}$ represents the total $CO_2$ emissions from electric towing (kg $CO_2$/year) and $EF_{grid}$ represents the emission factor of electricity (kg $CO_2$/kWh).

Similarly, the emission reduction achieved by implementing electric tow vehicle operation is determined by comparing it with the baseline taxiing scenario:

$$\Delta E = E_{baseline} - E_{ETT} \tag{3.4}$$

$$\%\, Reduction = \frac{\Delta E}{E_{baseline}} \times 100 \tag{3.5}$$

where $E_{baseline}$= emissions from conventional taxiing using aircraft engines

This approach enables a realistic evaluation of emission reduction potential by shifting energy use from onboard fossil fuel combustion to grid-based electricity. Given Nepal’s low-carbon electricity mix, electric towbar-less operation presents a highly effective strategy for reducing airport ground emissions.

### 3.5 Sensitivity Analysis

A sensitivity analysis was done to identify the robustness of the emission calculation model and to determine the effect of key operational parameters i.e. fuel flow rate and taxi time on the calculated taxi-out emissions at Tribhuvan International Airport (TIA). Sensitivity analysis is a systematic approach that is studied in environmental and engineering modelling that helps us to determine how variations in input parameters affect the output models. It helps us to identify the influential variables in the model and helps to evaluate the reliability of the model predictions under uncertain conditions and variable input conditions (Saltelli et al., 2007).

Aircraft taxi-out emissions are highly influenced by operational factors like number of engines used in operation, taxi duration and fuel supply rates. These parameters may change along with operational uncertainties like air traffic congestion, weather conditions, type of aircraft and engine as well as air traffic control procedures. Hence, sensitivity analysis guides researchers to assess the effect of such variations in the estimated emissions and determine which variables contribute more to emission variability while the input parameters change (Helton et al., 2006). A local one-at-a-time sensitivity analysis was done to study the variations of key input parameters on the calculated taxi-out carbon dioxide emissions. In this study, taxi-out time and fuel flow rate were varied independently while keeping the other parameters constant. The normalized sensitivity coefficient was calculated using equation (3.6).

$$S = \frac{\Delta E / E}{\Delta X / X} \tag{3.6}$$

where $S$ is the coefficient of sensitivity, $E$ is the baseline emission, $\Delta E$ stands for change in emission, $X$ is the selected input parameter, and $\Delta X$ is the change in the input parameter. This formulation is generally used in one-at-a-time sensitivity assessment to find out the relative effect of variation in the input variable on the model output (Saraiva et al., 2017). In this study, two key parameters were selected for sensitivity analysis that has direct influence on carbon dioxide emission on the aircrafts i.e. taxi-out time and engine fuel flow rate.

#### 3.5.1 Variation in taxi-out time

Taxi-out time is considered one of the most influential factors for aircraft ground emissions as the engines of the aircraft continue to burn fuel at idle thrust during the overall taxiing period. Longer taxi-out durations that may occur due to airport congestion or delay in the departures increases the overall fuel consumption and carbon dioxide emissions associated with it. To evaluate the influence of taxi-out time on $CO_2$ emissions, the baseline taxi-out time obtained from the operational flight data was varied from -20% to +20%. This range represents the typical variations which may occur due to operational inefficiencies, traffic congestion or improvement in surface traffic management. The resulting changes in fuel consumption which ultimately affects the $CO_2$ emissions were then calculated and compared with the baseline scenario. Previous studies have concluded the influence of taxi-out time in aircraft ground emissions that can account for a significant portion of airport surface emissions specially at congested airports (Nikoleris et al., 2011), (Stettler et al., 2018).

### 3.5.2 Variation in fuel flow rate

Fuel flow rate is defined as the amount of fuel consumed by aircraft engines under different conditions. Although standard fuel flow values are available from the ICAO Landing and Take-Off (LTO) emissions database, the rate of actual fuel consumption may vary on the basis of type of aircraft engine, maintenance condition of the aircraft, ambient air temperature as well as the operational procedures. The fuel flow rate used in the emission estimation model was varied with in the range of -20% to +20% to study the influence of fuel flow rate on the calculated carbon dioxide emissions. This approach determines the degree of extent to which uncertainties in fuel consumption assumptions affect the overall emission estimates. Similar sensitivity analyses have been conducted in airport emission studies to evaluate the reliability of fuel-based emission estimation methods (Winther et al., 2015), (Koudis et al., 2017).

The results obtained from the sensitivity analysis provide insights into the relative importance of different operational parameters that affects taxi-out emissions at TIA. Identifying the most influential variables helps to improve the accuracy of emission estimation models and helps to find out the best mitigation strategies to reduce aircraft ground emissions during taxi-out operation.

## 3.6 Economic evaluation

An economic evaluation was conducted to assess the financial feasibility and potential economic benefits of implementing emission reduction strategies for aircraft taxi-out operations at Tribhuvan International Airport (TIA). Economic assessment is an important component in aviation environmental studies because emission mitigation strategies must be both environmentally beneficial and economically viable for airlines and airport operators (Stettler et al., 2018). Therefore, the present study evaluates the economic implications of alternative taxi-out scenarios by estimating fuel savings, associated monetary benefits, and the potential payback period for advanced ground operation technologies.

### 3.6.1 Total fuel saving

Fuel savings per departure were estimated by comparing fuel consumption during taxi-out operations under the baseline dual-engine taxi scenario with the fuel consumption under alternative mitigation strategies such as single-engine taxiing and electric towing. Taxiing fuel consumption depends primarily on taxi duration and engine fuel flow rate. By reducing engine operation during taxiing, significant reductions in fuel burn can be achieved. Previous studies have shown that operational improvements such as single-engine taxiing can lead to noticeable reductions in fuel consumption during aircraft ground operations (Nikoleris et al., 2011). The fuel savings per flight were therefore calculated as the difference between the baseline fuel consumption and the fuel consumption under the mitigation scenario.

### 3.6.2 Annual fuel savings for Nepal Airlines Corporation

Annual fuel savings were estimated by multiplying the fuel savings per departure by the total number of departures of Nepal Airlines Airbus A330 and A320 aircraft from TIA within the study period. This approach allows the estimation of total fuel savings achieved over a year if the mitigation strategy were implemented consistently across all departures. Such analyses are commonly used in airport emission studies to quantify the operational and economic benefits of emission reduction strategies (Winther et al., 2015).

### 3.6.3 Economic benefits from $CO_2$ reduction

The economic value of emission reduction was estimated by assigning a monetary value to the reduced carbon dioxide emissions along with the fuel savings. Carbon pricing or the social cost of carbon is frequently used in environmental economic studies to quantify the financial value associated with emission reductions (Nordhaus, 2017). The total reduction in $CO_2$ emissions obtained from the mitigation scenarios was multiplied by an appropriate carbon price to estimate the monetary benefit of emission reduction.

The annual financial benefit was calculated from the difference between baseline and scenario fuel consumption multiplied by the unit fuel price as represented in equation (3.7).

$$B = \Delta F \times P_f = (F_{base} - F_{scenario}) \times P_f \tag{3.7}$$

### 3.6.4 Payback period for electric towing technology

The economic feasibility of adopting electric towbar-less tractor systems is evaluated by estimating the indicative payback period. The payback period represents the time required for the cost savings generated by reduced fuel consumption to offset the initial investment cost of the technology. Electric towing systems have been proposed as an effective strategy for eliminating aircraft engine usage during taxiing and significantly reducing ground-level emissions (Stettler et al., 2011). However, the implementation of electric technologies requires larger capital investment in purchasing specialized ground handling equipment. The payback period was then calculated by dividing the estimated investment cost by the annual operational savings resulting from reduced fuel consumption. From this economic evaluation, the study determines the financial viability for implementing different taxi-out emission reduction strategies at TIA. The results support the identification of cost-effective mitigation options that can simultaneously reduce fuel consumption, operating costs, and carbon emissions in airport ground operations.

# CHAPTER FOUR: RESULTS AND DISCUSSION

## 4.1 Annual flights operation

The number of flights provides an important operational indicator as it directly influences taxi-out time, fuel consumption during ground operations, and the resulting aircraft emissions. The aircraft considered in this analysis include two aircrafts i.e. Airbus 330 and Airbus 320 operated by Nepal Airlines Corporation (NAC). The annual number of international flight operations departed from TIA from the year 2020 to 2024 is represented in Figure 4.1.

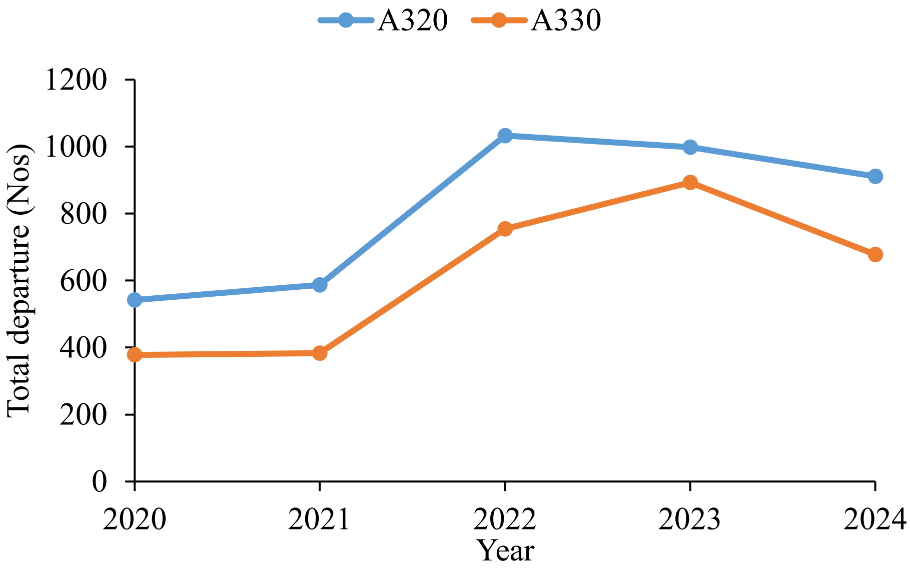

Figure 4.1: Annual flights departed from TIA

The results indicate that A320 aircraft consistently recorded a higher number of departures than A330 aircraft throughout the study period. In 2020, A320 departures were 540 flights, whereas A330 departures were around 380 flights. An increase in number of flights for A320 aircraft was seen in 2021, while A330 departures remained nearly constant. The number of flights increased rapidly in 2022, where A320 had 1033 flights and A330 departures increased to 750 flights. This rise in number of departures was observed after the recovery of aviation activities following the reduction of global travel restrictions and increased passenger demand due to 2020 and 2021 COVID pandemic. The higher number of flights continued into 2023, with A330 aircraft reaching their highest recorded departures of approximately 900 flights, while A320 departures remained close to 1000 flights.

In the year 2024, a slight decline in departures for both aircraft types was observed. A320 departures decreased to 920 flights, whereas A330 departures declined to 680 flights. This variation may be associated with seasonal changes in airlines scheduling, operational adjustments as well as route optimization. In a nutshell, the results show the strong growth in aircraft movements between 2021 and 2023, followed by a slight decline in 2024. As aircraft taxi-out emissions are directly proportional to the number of aircraft departures and taxi-out duration, the increase in aircraft movements during the peak demand years are the main contributor to higher taxi-out fuel consumption and associated carbon dioxide emissions.

### 4.2 Mean taxi-out time per departure

Taxi-out time represents the duration between aircraft pushback from the gate and the commencement of take-off roll, during which aircraft engines operate at idle thrust and continue to consume fuel. The mean taxi-out time of the international aircrafts operated by Nepal airlines form the year 2020 to the year 2024 were studied. Figure 4.2 represents the average taxi-out time per departure for Airbus A320 and Airbus A330 aircraft operating at Tribhuvan International Airport (TIA) from 2020 to 2024.

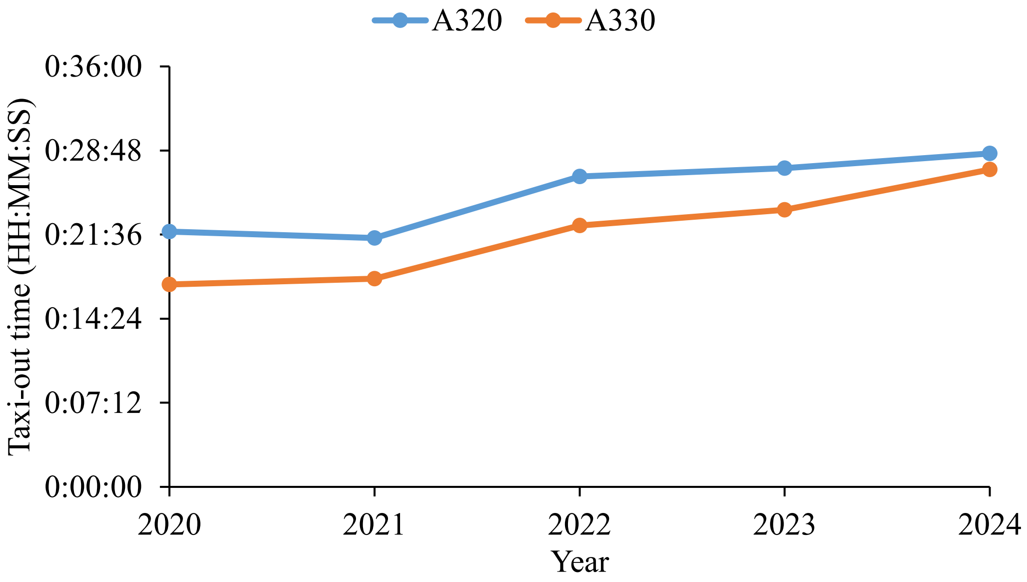

Figure 4.2: Average taxi-out time of the aircrafts

The results show that A320 aircraft consistently experienced slightly higher average taxi-out times than A330 aircraft throughout the study period. In 2020, the average taxi-out time for A320 aircraft was approximately 21 minutes, while A330 aircraft recorded a mean taxi-out duration of around 17 minutes. A slight decrease in taxi-out time for

A320 aircraft was observed in 2021, while the taxi duration for A330 aircraft remained nearly unchanged. An increase in taxi-out time was observed 2022 onward for both aircraft types. The mean taxi-out time for A320 aircraft increased to 25 minutes in 2022, while A330 aircraft reached 21 minutes during the same period. This trend continued through 2023 and 2024, where A320 taxi-out times gradually increased to nearly 28 minutes, and A330 taxi-out times rose to approximately 26 minutes.

The increasing trend in taxi-out time may be attributed to rising aircraft movements, airport congestion, and operational delays during peak traffic periods at TIA. Longer taxi durations indicate extended engine idle operation, which leads to increased fuel consumption and higher carbon emissions during ground operations. Hence, understanding variations in taxi-out time is essential for evaluating aircraft ground emissions and identifying operational inefficiencies. The results indicate that average taxi-out time has increased gradually between 2021 and 2024, suggesting growing congestion or operational complexity in airport surface movements. Since taxi-out emissions are directly proportional to engine operating time, the observed increase in taxi duration plays a significant role in the overall growth of taxi-related emissions.

### 4.3 Comparative carbon emission trends: A320 vs. A330

The carbon footprint of Nepal Airlines' fleet at Tribhuvan International Airport (TIA), specifically comparing the narrow-body Airbus A320 and the wide-body Airbus A330 from 2020 to 2024 were evaluated initially. The total annual carbon emissions (Tons) for both aircraft types are illustrated in Figure 4.3. Between 2020 and 2021, emissions remained relatively low and stable, likely reflecting the global stagnation in aviation due to COVID-19 travel restrictions. However, a sharp upward trajectory is observed starting in 2022.

- **Airbus 330:** The wide-body aircraft exhibited a significant surge, peaking in 2023 at approximately 3,500 tons of $CO_2$. This suggests an increase in long-haul flight frequencies or higher payload factors during the COVID-19 post-pandemic recovery phase.
- **Airbus 320:** The narrow-body fleet followed a similar growth pattern, its total annual emissions were substantially lower than the A330, stabilizing around 1,300 tons after 2022.

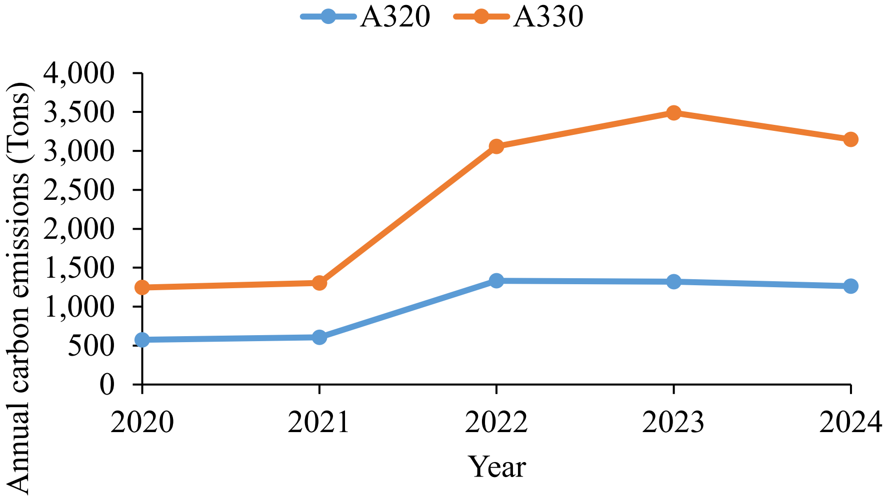

Figure 4.3: Annual carbon emission from the aircrafts

Although the annual emissions provide a sense of scale, the average carbon emissions (Tons per flight/operation) were also studied to calculate the mean emission generated by each of the aircraft during taxi-out operation. The average carbon emission generated by individual aircraft annually is represented in  Figure 4.4.

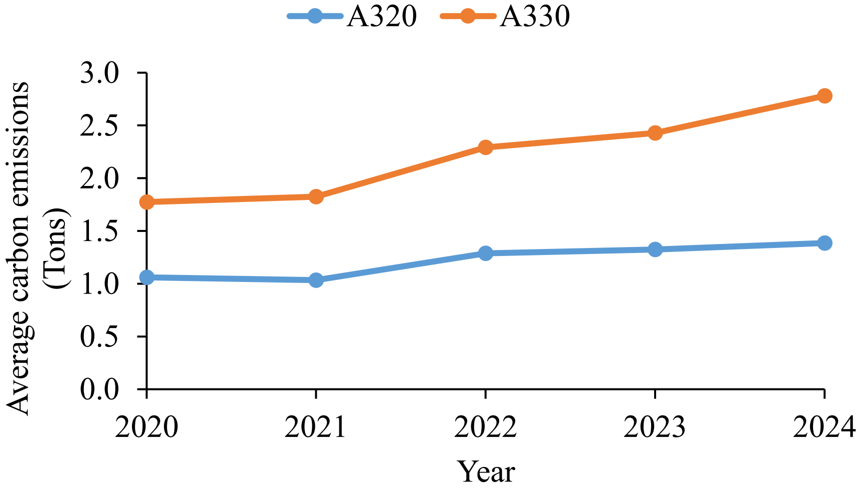

Figure 4.4: Mean carbon emission generated by individual aircrafts

From the average carbon emission graph illustrated above for individual aircrafts, different conclusion has been drawn from the trendline of the aircrafts

- **Disparity in Efficiency:** The A330 consistently produces higher average emissions compared to the A320. By 2024, the average emission for an A330 operation approached 2.8 tons, whereas the A320 remained below 1.5 tons.

- **Increasing Trends:** Interestingly, both aircraft show a steady increase in average emissions per operation from 2021 onwards. This trend could be attributed to several factors, including:
    - Increased air traffic congestion at TIA leading to longer holding times.
    - Heavier passenger/cargo loads as demand returned to 100% capacity.
    - Aging factors impacting fuel burn efficiency.

The data indicates that while the A320 is more carbon-efficient per operation due to its smaller size, the A330's contribution to the total carbon footprint of Nepal Airlines at TIA is dominant, primarily driven by its higher fuel consumption requirements for wide-body operations.

### 4.4 Seasonal variation for the taxi-out time

Seasonal variation of the taxi-out time was evaluated by analyzing monthly changes in both the flight frequency (total departures) and mean taxi-out time corresponding to it. As taxi-out delay is directly associated with ground congestion and operational conditions, the variation in departures was examined first that was followed by its impact on taxi-out time.

#### 4.4.1 Monthly variation in departures

The monthly departures of the aircrafts show a distinct seasonal trend where aircraft A320 departures increase from 55 flights in January to a peak range of 90-105 flights during July-October and then decreases to 76 flights in December. A330 departures remain quiet stable ranging from 40-80 flights, with a minimum during August-September with 40-42 flights. This variation indicates higher traffic density during mid-year and early autumn season annually. Increased aircraft movements during these months causes congestion at taxiways and holding points, that directly contributes to increase in ground delay. As fuel consumption during taxi-out operation is directly dependent with the taxi-out time, higher traffic months contribute to increased fuel consumption along with increase carbon dioxide emissions. The monthly departure trend for the aircrafts A330 and A320 is given in Figure 4.5.

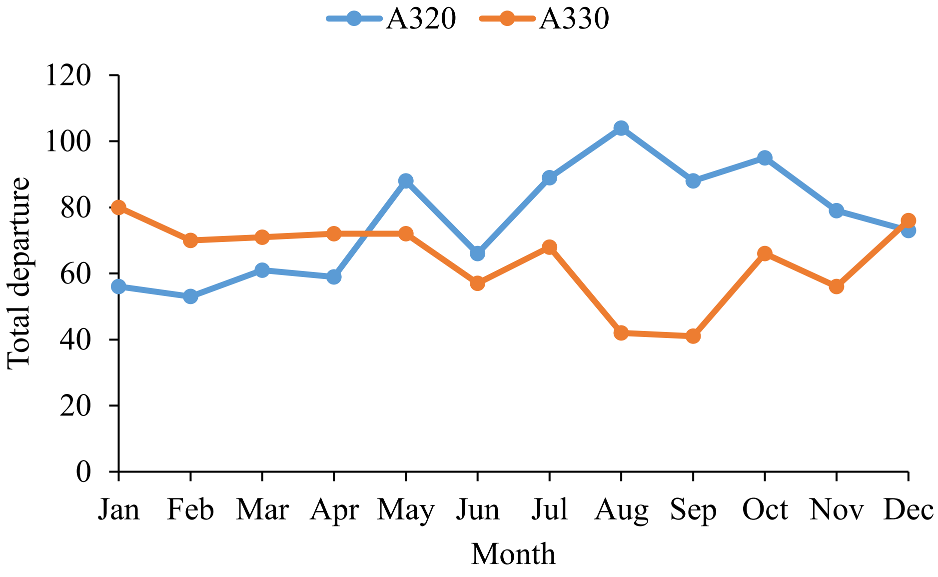

Figure 4.5: Monthly departures of the aircrafts

### 4.4.2 Monthly variation in mean taxi-out time

The mean taxi-out time trend was found to be consistent along with the variation in departures. For A320, the taxi-out time increases from 22-24 minutes in January to the peak of 36-37 minutes in October that reduces to 25 minutes in December. A330 shows a narrower variation that ranges from 24 to 30 minutes. The peak taxi-out time was observed in October. The monthly trend for taxi-out time is represented in Figure 4.6.

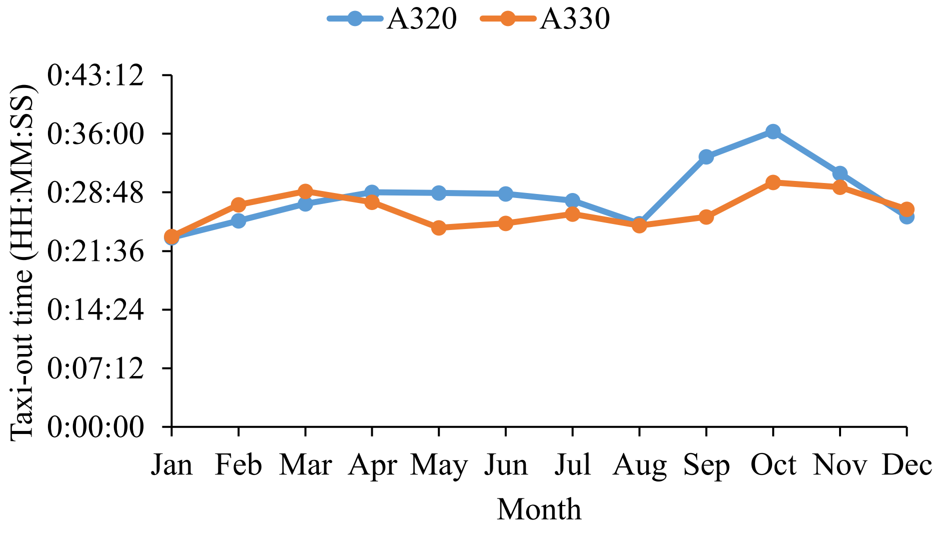

Figure 4.6: Monthly taxi-out trend

A direct relationship was observed between departures and taxi-out time:

- Higher departures (July-October) → higher taxi-out time
- Lower departures (January-March, November-December) → lower taxi-out time

This confirms that taxi-out delay is primarily driven by traffic congestion. The higher variability in A320 taxi-out time is attributed to its higher operational frequency. Increased taxi-out duration during peak months results in higher fuel consumption and emissions, which is significant for seasonal carbon accounting.

### 4.5 Relationship between taxi-out time and aircraft movements

The variation in taxi-out time is often influenced by the number of aircraft movements and airport surface congestion. As air traffic increases, aircraft experience longer waiting periods on taxiways and at runway holding points before take-off clearance is granted. Therefore, analyzing the relationship between aircraft movements and taxi-out time is important for understanding operational inefficiencies and their impact on fuel consumption and emissions. During the study period (2020–2024), the average taxi-out time for both Airbus A320 and Airbus A330 aircraft shows a gradual increasing trend. In 2020 and 2021, taxi-out durations remained relatively lower, which can be attributed to reduced air traffic movements during the COVID-19 pandemic period, resulting in less congestion on airport taxiways. As flight operations resumed and air traffic gradually increased from 2022 onwards, the taxi-out time also increased correspondingly.

For the Airbus A320 fleet, the taxi-out time increased from approximately 21 minutes in 2020 to nearly 28 minutes in 2024, indicating a rise in ground movement delays. Similarly, Airbus A330 aircraft showed an increase from around 17 minutes in 2020 to approximately 26 minutes in 2024. Although A330 aircraft consistently recorded slightly lower taxi-out times compared to A320 aircraft, both aircraft categories exhibited similar upward trends over the five-year period.

The increase in taxi-out duration is primarily associated with higher aircraft movements, runway queuing, and operational constraints within the airport surface network. Tribhuvan International Airport operates with limited taxiway infrastructure and a single runway, which can create bottlenecks during peak departure periods. As a result, aircraft may spend longer periods idling on taxiways while waiting for departure clearance. Longer taxi-out times have direct implications for fuel consumption and carbon emissions, since aircraft engines continue to operate during taxiing at idle thrust conditions. Consequently, increased ground delay contributes to higher operational costs for airlines and increased environmental impacts. Understanding the relationship between aircraft movements and taxi-out time therefore provides an important basis for evaluating potential mitigation strategies such as optimized taxi procedures, improved surface traffic management, or the adoption of electric taxiing technologies. The observed trend suggests that airport congestion and increasing flight operations are key factors influencing taxi-out duration at Tribhuvan International Airport, which subsequently affects the fuel consumption and emission levels associated with aircraft ground operations.

### 4.6 Statistical validation of the model

To assess the reliability of the observed taxi-out time, fuel consumption and emission trends, a Multiple Linear Regression (MLR) analysis was performed for both the Airbus A320 and A330 fleets. This analysis quantified that the operational variables like annual departures, ground taxi-out times statistically drive the carbon footprint at TIA.

#### 4.6.1 Model fit and reliability

The regression statistics indicate an exceptionally high degree of correlation for both aircraft types. As represented in Table both models achieve an R-Square value exceeding 0.99, meaning that over 99% of the variance in average emissions is explained by the chosen operational predictors.

Table 4.1: Comparative regression statistics

| Parameter | Airbus A320 | Airbus A330 |
|---|---|---|
| Multiple R | 0.9996 | 0.9997 |
| $R^2$ | 0.9992 | 0.9994 |
| Adjusted $R^2$ | 0.9984 | 0.9988 |
| Standard error | 0.0063 | 0.0141 |

The lower standard error for the A320 (0.0063) compared to the A330 (0.0141) suggests that the narrow-body fleet's emission profile is slightly more predictable under TIA's current operational constraints.

### 4.6.2 Analysis of Variance (ANOVA)

To evaluate the statistical significance of the regression models developed for the Airbus A320 and A330 fleets, an Analysis of Variance (ANOVA) was performed. This process tests the null hypothesis that the operational variables (Annual Departures and Average Taxi Time) have no influence on the carbon emissions. For both aircraft, the significance F values are well below the alpha level of 0.05 (A320: 0.00077; A330: 0.00055), indicating that the results are highly significant and unlikely to have occurred by chance.

- A320 Significance: The F-statistic of 1293.12 confirms a massive ratio of explained variance to unexplained error.
- A330 Significance: The even higher F-statistic of 1804.22 underscores the extreme sensitivity of wide-body emissions to the operational variables studied.

### 4.6.3 Residual analysis and predictive accuracy

The accuracy of the regression models is further validated by the Residual Output, which measures the deviation between actual observed emissions and the model's predicted values.

- A320 Precision: Residuals for the A320 are minimal, ranging from -0.0056 to +0.0053. The model was most accurate in the final observation year (2024), with a residual of only -0.00024.
- A330 Precision: While the A330 residuals are slightly higher (ranging from -0.0103 to +0.0121), they remain remarkably low given the higher volume of total emissions.
- Operational Conclusion: The consistent closeness of the predicted average emissions to the actual recorded values confirms that these models can be used by airport authorities to accurately forecast the carbon impact of future flight schedule changes or ground infrastructure improvements.

### 4.7 Global best practices for taxi-out emission reduction

Single-engine taxiing (SET) has been widely studied and shown to reduce fuel burn and associated $CO_2$ emissions by up to 50% compared with dual-engine operations in some contexts, depending on taxi procedures and flight segment characteristics (Stettler et al., 2011). Electric taxiing solutions such as electric towing vehicles or on-board electric taxi systems significantly lower local emissions and reduce fuel use, as indicated by recent multi-airport analyses (Maciejewska & Kurzawska-Pietrowicz, 2025). Optimizing ground traffic management through taxi path optimization and surface surveillance technologies contributes to reduced congestion and shorter taxi distances, thereby lowering taxi fuel consumption and emissions (Chen et al., 2024), (Burgain et al., 2013). Table 4.2 evaluates the applicability of these practices at TIA, considering infrastructure, operational complexity, and cost. presents a comparison of key global practices and technologies investigated in the literature for reducing aircraft taxi-out emissions.

Table 4.2: Global best practices for taxi-out emission reduction

| Strategy | Reduction potential | Evidence | Applicability to TIA |
|---|---|---|---|
| Single-Engine Taxiing (SET): Taxiing aircraft with only one engine (half the thrust) to reduce fuel burn | 7-50% reduction in fuel and emissions compared to dual-engine taxiing (Stettler et al., 2018) | London Heathrow, multi-aircraft studies | High- needs procedural change; low investment cost |
| Electric Taxis / EGTS: On-board electric motor drives aircraft taxi without main engines | Significant reduction, electric taxi vehicles show near-zero local emissions (Maciejewska & Kurzawska-Pietrowicz, 2025) | Warsaw & Poznan airport modeling (electric towing) | Medium – it requires large investment and advanced equipment |

| Strategy | Reduction potential | Evidence | Applicability to TIA |
|---|---|---|---|
| External Electric Towing Vehicles (ETVs): Use electric or e-tugs to push/tow aircraft, engines off | $CO_2$, $NO_x$ and other gases greatly reduced (Zoutendijk et al., 2023) | Airports evaluating electric towing deployment | High - depends on cost & infrastructure |
| Improved Surface Traffic Management: Taxi path optimization and air traffic control sequencing | Reduces taxi time and emissions by reducing congestion conflicts (Chen et al., 2024) | Case studies showing reduced conflicts and fuel use | High - ATC process improvement |
| Advanced Surveillance & Spot Control: Use of surface surveillance systems to manage departures and taxi movements | 4–6% reduction in taxiway aircraft emissions (Burgain et al., 2013) | Boston Logan, Seattle-Tacoma airports | Medium - needs surveillance investment |

### 4.8 Scenario analysis of taxi-out emission reduction

#### 4.8.1 Baseline scenario

The baseline scenario represents the data of the year 2024 operating under dual-engine taxi operations at TIA with an average taxi-out time of 28.4 minutes and total annual emissions of 1,014,933 tons $CO_2$. Under the baseline scenario, the emissions done by two types of aircrafts till the year 2030 is forecasted. The mean annual emissions done by the aircrafts during a single taxi-out operation up to the year 2030 is represented in Figure 4.7.

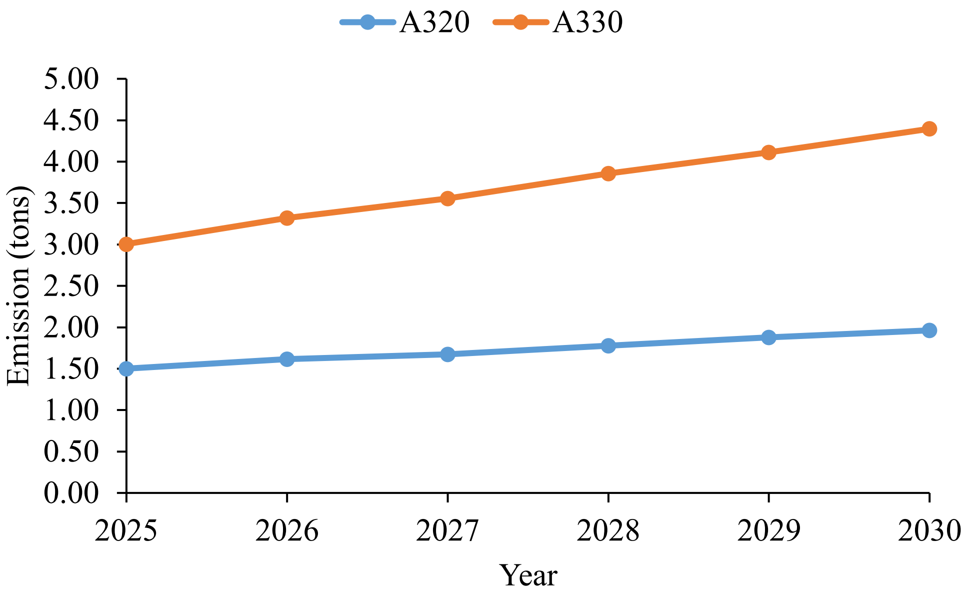

Figure 4.7: Baseline scenario for emissions of the aircrafts

### 4.8.2 Single engine taxiing scenario

Studies indicate that single engine taxiing can reduce fuel consumption of airbus A320 by 21.1% under each flight (Kameníková et al., 2022). Similarly, $CO_2$ emission reduction was found to be 33.39% using SET in airbus A330. The implementation of single engine taxiing can further reduce the fuel flow at TIA and reduce the overall emissions emitted by the aircraft. The mean carbon emission that would be produced by an individual aircraft during taxi-out operation up to the year 2030 on the two models of aircraft using single engine taxiing method is represented in Figure 4.8.

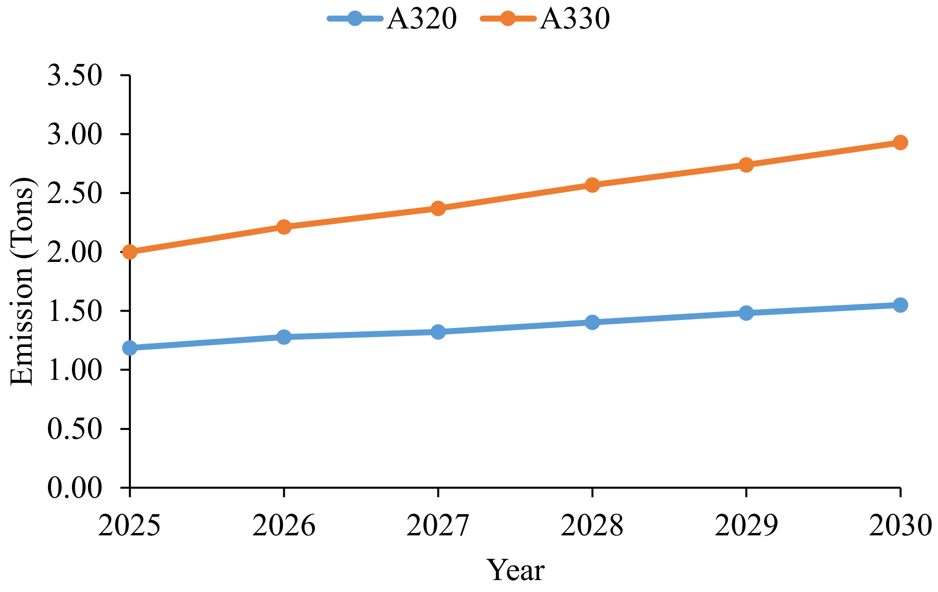

Figure 4.8: Emission projection under SET scenario

The data reveals a consistent linear escalation in carbon output for both fleet type, reflecting an anticipated increase in ground operational cycles over the forecast period. A critical observation is the significant disparity in emission magnitudes between the two aircraft classes; the wide-body A330 initiates the period with a mean emission of approximately 2.0 tons in 2025, which is nearly 1.6 times higher than the 1.19 tons projected for the narrow-body A320. This variance is fundamentally attributed to the higher bypass ratios and thrust requirements of the A330's power plants, which necessitate a greater fuel flow even when operating in a reduced-engine taxiing configuration.

Analytically, the slope of the emission curve for the A330 is notably steeper than that of the A320, indicating a more rapid accumulation of environmental impact as fleet utilization scales. By the year 2030, the A330 is projected to reach an emission peak of approximately 2.93 tons, representing a 46% increase from the baseline year, whereas the A320 reaches a more moderate 1.55 tons. This divergence suggests that while the SET strategy effectively lowers the per-minute fuel burn compared to traditional dual-engine taxiing, the absolute emission levels remain heavily sensitive to aircraft MTOW (Maximum Take-Off Weight) and engine specifications. Consequently, for wide-body operations, SET serves as a vital mitigation tool, yet the rising trend underscores that operational efficiencies alone may be insufficient to offset the emissions generated by the projected growth in air traffic demand without the integration of supplemental decarbonization technologies.

### 4.8.3 Electric tow vehicles

This scenario implements the use of electric tow vehicles for towing the aircraft during ground operation. At present, these operations are done by using tow vehicles operating using diesel fuel. The annual fuel consumption by the tow vehicle from the year 2020 to 2024 obtained from the ground operations report of NAC is represented in Table 4.3.

Table 4.3: Annual diesel consumption by towbar vehicles (2020-2024)

| Year | Annual diesel consumed (Liters) | |
|---|---|---|
| | Airbus A320 | Airbus A330 |
| 2020 | 3475 | 5791 |
| 2021 | 4937 | 8228 |
| 2022 | 8513 | 14188 |
| 2023 | 9284 | 15474 |
| 2024 | 8912 | 14853 |

From the data obtained from the operation section and using the emission factor for diesel fuel, the annual emission done by the tow vehicles while operating under baseline scenario is given in Table 4.4.

Table 4.4: Annual $CO_2$ emissions by the tow vehicles under baseline scenario

| Year | Baseline emission (tons) | |
|---|---|---|
| | A320 | A330 |
| 2020 | 9.03 | 15.06 |
| 2021 | 12.84 | 21.39 |

| Year | Baseline emission (tons) | |
|---|---|---|
| | A320 | A330 |
| 2022 | 22.13 | 36.89 |
| 2023 | 24.14 | 40.23 |
| 2024 | 23.17 | 38.62 |
| 2025 | 30.14 | 50.23 |
| 2026 | 33.17 | 55.29 |
| 2027 | 34.97 | 58.29 |
| 2028 | 38.62 | 64.37 |
| 2029 | 42.74 | 71.23 |
| 2030 | 45.12 | 75.20 |

Emissions from tow vehicles during A320 ground operations increase from 9.03 tons in 2020 to 45.12 tons by 2030, while A330 emissions rise more sharply from 15.06 tons to 75.20 tons over the same period, reflecting the higher fuel consumption associated with larger aircraft. A gradual increase is observed from 2020 to 2023, followed by a slight decline in 2024, which may be attributed to operational fluctuations or reduced flight activity. However, from 2025 onward, emissions exhibit a consistent and significant growth trajectory, driven by projected increases in flight operations and corresponding towing requirements. Overall, A330 consistently contributes a larger share of emissions compared to A320, and the widening gap between the two aircraft categories highlights the growing environmental burden of wide-body aircraft ground operations under a diesel towbar less vehicle scenario.

The implementation of electric tow vehicle would lead the airlines to reduce the total carbon dioxide emissions for A320 decrease from 33.17 tons to 4.95 tons in 2026 while A330 emissions drop from 55.29 tons to 4.09 tons in 2026 and increase to only 6.84 by 2030. Despite the gradual increase in absolute emissions over time-likely driven by projected growth in flight operations-the relative emission reduction remains remarkably high, exceeding 83% for A320 and 90% for A330 throughout the period. Similarly, the reduction efficiency is consistently higher for A330, indicating that electrification yields greater environmental benefits for wide-body aircraft due to their higher baseline fuel consumption. However, a slight declining trend in percentage reduction is observed for both aircraft types (A320: 85.09% to 83.68%; A330: 92.60% to 90.91%), suggesting that increasing operational demand may partially offset efficiency gains if not accompanied by further improvements in energy sourcing or operational optimization. The results demonstrate that electric towbar less technology offers a highly effective decarbonization pathway, though its long-term sustainability impact will depend on managing demand growth and ensuring low-carbon electricity supply. The total carbon emission from the towbar less vehicles is represented in Figure 4.10.

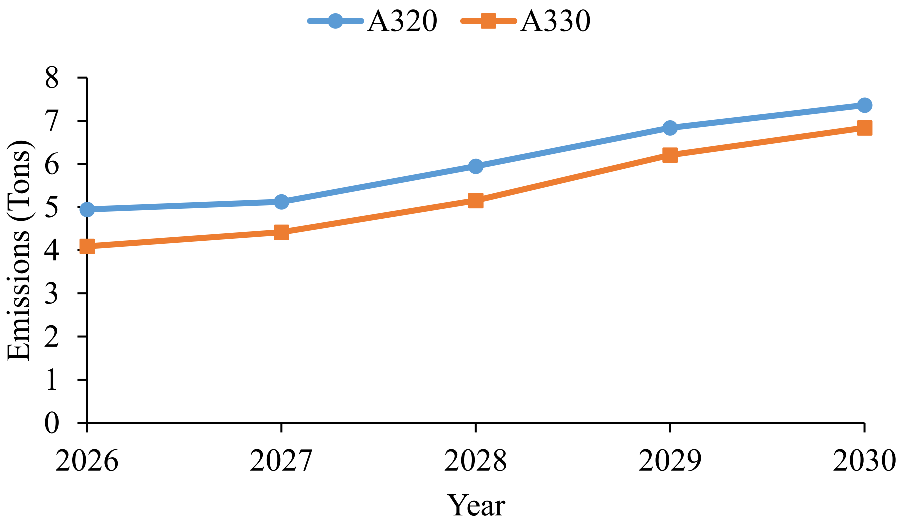

Figure 4.9: $CO_2$ emissions using electric tow vehicles

### 4.9 Sensitivity analysis

Sensitivity analysis was conducted to evaluate the influence of key operational parameters on aircraft ground operation emissions during taxi-out. The analysis focused on two primary variables: taxi-out time and fuel flow rate, which are considered critical determinants of fuel consumption during aircraft ground operations. Variations of ±20% from the baseline values were applied to each parameter to examine their effect on carbon emissions for A320 and A330 aircraft types.

### 4.9.1 Sensitivity to taxi-out time

Taxi-out time represents the duration an aircraft spends moving from the gate to the runway prior to takeoff. Prolonged taxiing leads to increased fuel consumption and consequently higher emissions. In this study, taxi-out time was varied between −20% and +20% relative to the baseline value, and the corresponding emissions were calculated for A320 and A330 aircraft. A reduction of taxi-out time by 20% decreases emissions to 8.35 tons for A320 and 12.49 tons for A330 annually, while an equivalent increase of 20% raises emissions to 12.53 tons and 18.73 tons, respectively. This symmetric variation indicates a strong proportional relationship between taxi duration and fuel consumption. Figure 4.10 illustrates the variation in carbon emissions for A320 and A330 aircraft under different taxi-out time conditions ranging from −20% to +20% relative to the baseline value.

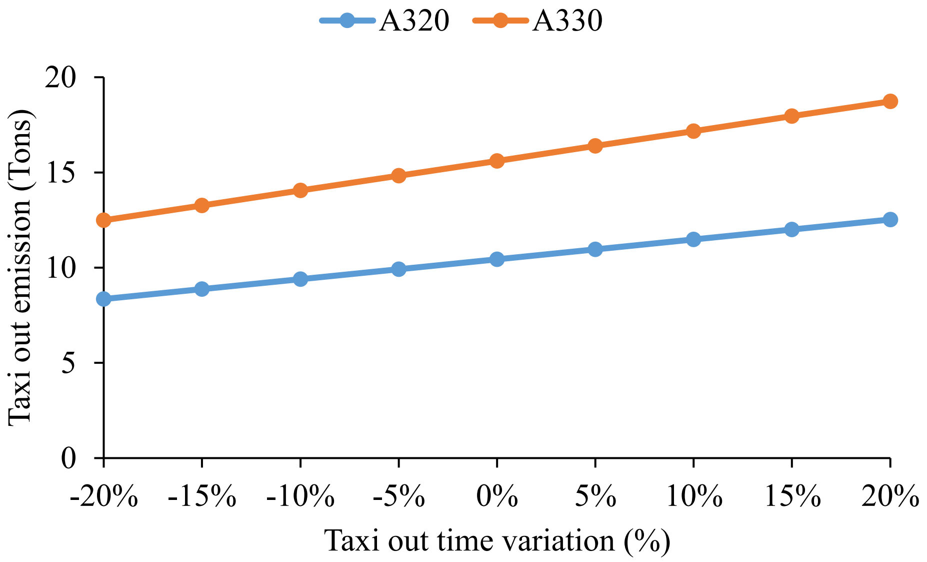

Figure 4.10: Sensitivity of $CO_2$ variation to taxi-out time variation

The linear trend observed in the figure confirms that taxi-out time is a highly sensitive operational parameter influencing aircraft ground operation emissions. Longer taxi durations lead to greater fuel burn due to extended engine operation at idle thrust, thereby increasing carbon emissions. Similar findings have been reported in previous aviation emission studies, where taxi delays were identified as a significant contributor to airport ground emissions.

### 4.9.2 Sensitivity to fuel flow rate

A similar sensitivity analysis was conducted by varying the fuel flow rate during taxi-out operations by ±20%. Fuel flow rate represents the amount of fuel consumed per unit time by aircraft engines while operating at idle or low thrust during taxiing. The results showed that emissions responded proportionally to changes in fuel flow rate, producing the same emission variation pattern observed in the taxi time analysis. This occurs because emissions are directly proportional to both taxi time and fuel flow rate in the emission estimation model. Consequently, a ±20% variation in fuel flow rate resulted in approximately ±20% variation in emissions for both aircraft types. Figure 4.11 represents the sensitivity of carbon emissions to variations in fuel flow rate during taxi operations for A320 and A330 aircraft. The fuel flow rate was varied within a range of −20% to +20%, and the corresponding emissions were calculated using the emission estimation model.

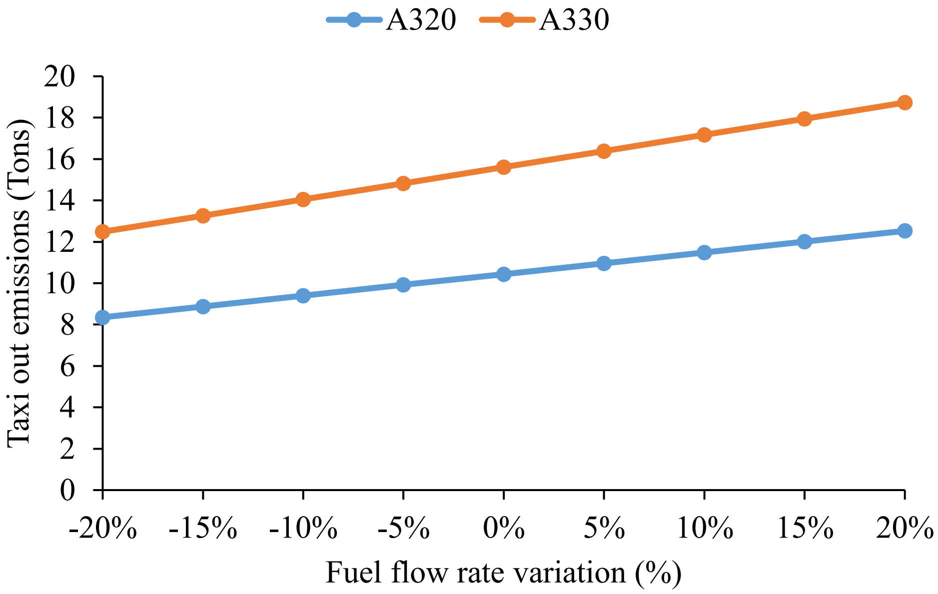

Figure 4.11: Sensitivity of $CO_2$ emissions to fuel flow rate variation

The results demonstrates that $CO_2$ emissions increase proportionally with increasing fuel flow rate. At a −20% reduction in fuel flow rate, emissions decrease to 8.35 tons for A320 and 12.49 tons for A330, whereas a +20% increase results in emissions of 12.53 tons and 18.73 tons, respectively. The identical trend observed in both the taxi time and fuel flow sensitivity analyses is due to the direct proportional relationship between these parameters in the emission estimation model.

Overall, the sensitivity analysis confirms that both taxi-out time and fuel flow rate exhibit a nearly linear relationship with carbon emissions, indicating that improvements in airport surface operation efficiency can significantly reduce aircraft ground operation emissions. Operational strategies such as single-engine taxiing and improved engine management have been widely recommended to minimize fuel burn during ground operations (Khadilkar & Balakrishnan, 2012).

## 4.10 Economic analysis

The economic analysis was performed to find out the annual fuel savings that would lead to annual financial saving for the airlines company. The economic evaluation was performed for single engine taxiing scenario where the fuel saving and financial benefits were also studied. The annual fuel saving under single engine taxiing scenario is represented in Figure 4.12.

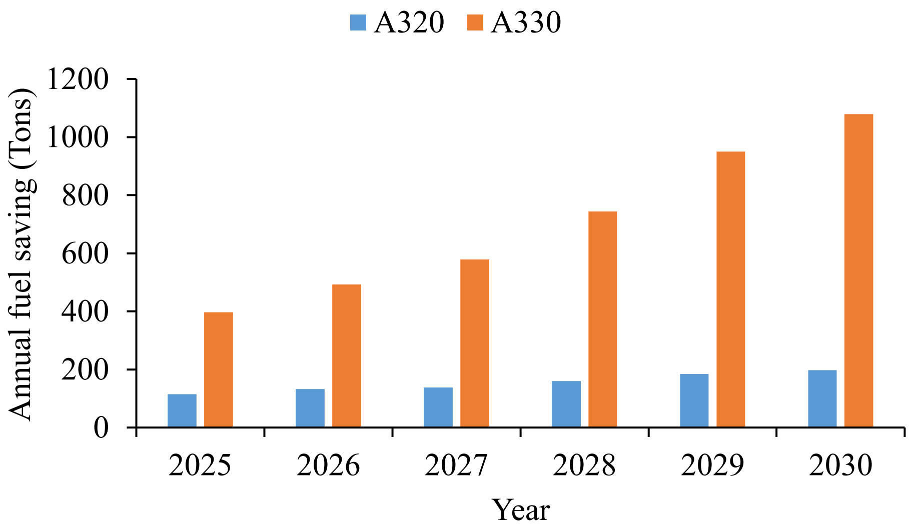

Figure 4.12: Annual fuel saving for single engine taxing scenario

For the A320 aircraft, the annual fuel savings increase gradually from approximately 100 tons in 2025 to about 190-200 tons by 2030. The relatively moderate increase reflects the lower fuel consumption characteristics and smaller engine capacity of the narrow-body A320 aircraft. In contrast, the A330 aircraft shows significantly higher fuel savings, increasing from around 400 tons in 2025 to approximately 1080 tons by 2030. This higher reduction is primarily due to the larger engine thrust requirements and higher fuel flow rates associated with wide-body aircraft, which result in greater fuel savings when one engine is shut down during taxi operations.

Overall, the figure indicates that wide-body aircraft benefit more substantially from the implementation of single engine taxiing compared to narrow-body aircraft. The results highlight the strong potential of SET as an operational strategy for reducing fuel consumption and associated emissions at airports, particularly for larger aircraft categories.

### 4.10.1 Annual price saving

For the A320 aircraft, the annual price savings increase gradually from approximately 18,000 thousand NPR in 2025 to around 32,000 thousand NPR by 2030. Although the increase is moderate, it reflects the consistent economic benefit of implementing single engine taxiing for narrow-body aircraft operations.

In contrast, the A330 aircraft demonstrates significantly higher economic savings, increasing from approximately 63,000 thousand NPR in 2025 to about 170,000 thousand NPR in 2030. The larger magnitude of savings for the A330 is attributed to its higher fuel consumption rate and larger engine capacity, which results in greater fuel reductions when operating under a single-engine taxiing procedure.

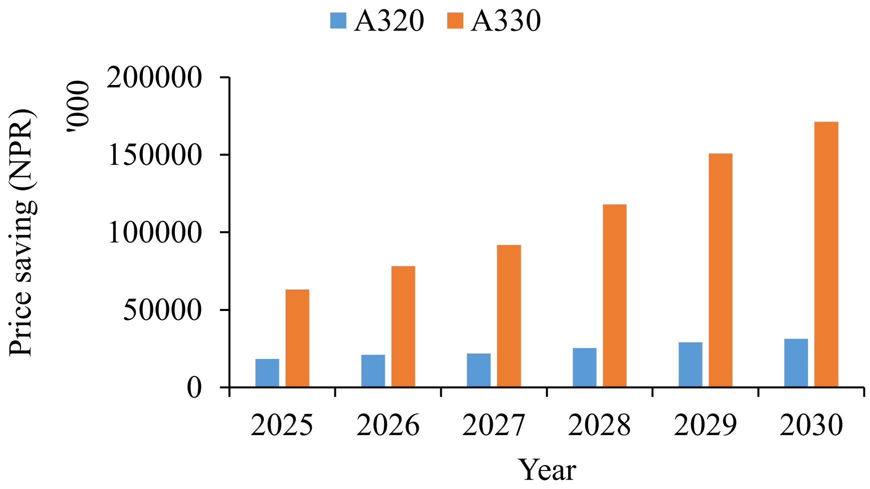

Figure 4.13: Annual price saving under single engine taxiing

Figure 4.13 presents the projected annual economic savings achieved through the implementation of single engine taxiing for A320 and A330 aircraft from 2025 to 2030. The results show a steady increase in cost savings over time, with A330 aircraft demonstrating significantly higher economic benefits due to their greater fuel consumption compared to A320 aircraft.

### 4.10.2 Cost benefit analysis for electric tow vehicle

A structured cost-benefit analysis was performed to evaluate the economic feasibility of implementing electric tow vehicles for aircraft ground operations. The analysis is based on a 10-year project life and a discount rate of 10%, incorporating updated fuel prices and actual fuel consumption data as represented in Table 4.5.

Table 4.5: Parameters for towbar vehicles electrification

| Parameter | Unit | Value |
|---|---|---|
| Project lifetime | years | 10 |
| Discount rate | % | 10 |
| Diesel price | NPR/liter | 204.5 |
| Electricity tariff | NPR/kWh | 12 |
| Carbon price | NPR/t$CO_2$ | 6,570 |
| Electric tractor base cost | NPR/unit | 29,885,420 |
| Import tax & duties | % | 40 |
| Number of vehicles | - | 2 |

A comparative analysis between the baseline scenario using diesel tow vehicles and electric tow vehicles is represented in Table 4.6 along with their financial indicators. The table highlights not only absolute values but also the economic transition achieved through towbar less vehicles electrification.

Table 4.6: Cost benefit analysis for electric towbar vehicles operation

| Parameter | Unit | Value |
|---|---|---|
| Investment and baseline comparison | | |
| Total capital investment | Million NPR | 83.68 |

| Parameter | Unit | Value |
|---|---|---|
| Diesel operating cost | Million NPR/year | 10.97 |
| Electric operating cost | Million NPR/year | 2.54 |
| Annual cost savings | Million NPR/year | 8.43 |
| Environmental and monetized benefits | | |
| Emission reduction | $tCO_2$/year | 70 |
| Carbon price | NPR/$tCO_2$ | 6570 |
| Carbon revenue | Million NPR/year | 0.46 |
| Financial viability indicators | | |
| Net Present Value (NPV) | Million NPR | -29.04 |
| Benefit Cost Ratio (BCR) | - | 0.65 |
| Payback period | years | 9.41 |
| Internal Rate of Return (IRR) | % | 4.65 |

The transition from diesel to electric tow vehicles lead the airlines towards substantial operational cost savings, primarily driven by the large difference in energy costs. The electric system reduces annual energy expenditure by NPR 7.53 million while additional savings of NPR 0.90 million is achieved through lower maintenance requirements. This results in a total annual operating cost reduction of NPR 8.43 million confirming that electrification significantly improves operational efficiency. The project is highly sensitive to fuel prices and capital cost structure. The recent increase in diesel price has already improved the economic outlook significantly by enhancing annual savings. Therefore, relatively small changes like reduced import duties, increased utilization rates can shift the project towards a positive NPV.

# CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

Following conclusions have been drawn from the study.

## 5.1 Conclusion

- The Airbus A330 recorded the highest annual emissions of 2167.78 tons of $CO_2$ in 2023 with 839 flights, while the Airbus A320 reached 1331.92 tons in 2022 with 1033 flights. Under per operation basis, the aircraft A330 shows higher emission intensity, with a projected mean emission of 3.18 tons for the year 2025 which is around 2.7 times higher than the airbus A320 (1.18 tons).
- A continued increase in taxi-out emissions for both aircrafts was observed while projecting $CO_2$ emission. The A330 is projected to emit 4.48 tons of $CO_2$ by 2030 which represents a 40% increase from the baseline year, whereas the emission from airbus A320 rise to 1.55 tons.
- Single-engine taxiing provides higher amount of fuel savings, with the aircraft A330 achieving reductions in emissions from 400 tons in 2025 to 1080 tons in 2030, and for the aircraft A320 emission reduces from 115.14 tons in 2025 to 197.89 tons in 2030. These improvements provide annual cost savings increasing from NPR 18 million to NPR 32 million for the A320, and from NPR 63 million to NPR 170 million for the A330.
- The adoption of electric tow taxiing technology reduces $CO_2$ emissions by 83% for A320 and 90% for A330 during taxi-out operations. The financial analysis indicates annual energy savings of NPR 7.53 million, a cost benefit ratio of 0.65, and a payback period of 9.41 years. This indicates that while the technology is environmentally effective, its large-scale implementation would require policy support, financial incentives, or carbon pricing mechanisms to enhance economic viability.

## 5.2 Recommendations

- Future research should utilize high-resolution data from QAR or FDR systems to obtain more accurate fuel burn and emission estimates during taxiing.
- The effect of altitude and weather correction factor can help to make the study more effective.

- Further studies must include the emissions during taxi-in process and consider other carbon emissions like $NO_x$, CO etc.
- Future studies should expand the scope to include emissions from all aircraft types and operators using the airport.

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# ANNEX

## Annex-1: Aircraft data collected from the Nepal Airlines

### A320: AKW

| Parameter | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Annual taxi out time (HH:MM:SS) | 102:18:00 | 93:01:00 | 170:36:00 | 266:13:00 | 247:49:00 |
| Annual number of Departure | 275 | 272 | 371 | 603 | 523 |
| Total Annual Carbon Emission (Kg) | 7150170:55:52 | 270888.3456 | 496830.8736 | 775291.085 | 721705.574 |
| Total Annual Carbon Emission (Tonn) | 297.92 | 270.89 | 496.83 | 775.29 | 721.71 |
| Average Carbon emission per Departure (Tonn) | 1.08 | 1.00 | 1.34 | 1.29 | 1.38 |

### A320: AKX

| Parameter | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---:|---:|---:|---:|---:|
| Annual taxi out time (HH:MM:SS) | 95:06:00 | 115:27:00 | 286:45:00 | 187:51:00 | 185:36:00 |
| Annual number of Departure | 267 | 315 | 662 | 395 | 388 |
| Total Annual Carbon Emission (Kg) | 276955.5456 | 336219.9552 | 835089.408 | 547067.29 | 540514.714 |
| Total Annual Carbon Emission (Tonn) | 276.96 | 336.22 | 835.09 | 547.07 | 540.51 |

| Parameter | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Average Carbon emission per Departure (Tonn) | 1.04 | 1.07 | 1.26 | 1.38 | 1.39 |

**A330: ALZ**

| Parameter | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Annual taxi out time (HH:MM:SS) | 52:32:00 | 43:37:00 | 152:32:00 | 174:36:00 | 141:45:00 |
| Annual number of Departure | 187 | 134 | 404 | 441 | 329 |
| Total Annual Carbon Emission (Kg) | 322714.37 | 267938.93 | 937018.37 | 1072574.78 | 870775.92 |
| Total Annual Carbon Emission (Tonn) | 322.71 | 267.94 | 937.02 | 1072.57 | 870.78 |
| Average Carbon emission per Departure (Tonn) | 1.73 | 2.00 | 2.32 | 2.43 | 2.65 |

**A330: ALY**

| Parameter | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Annual taxi out time (HH:MM:SS) | 56:39:00 | 70:15:00 | 128:45:00 | 178:17:00 | 165:13:00 |
| Annual number of Departure | 191 | 249 | 350 | 452 | 349 |
| Total Annual Carbon Emission (Kg) | 8352077:11:02 | 431548.56 | 790916.4 | 1095201.65 | 1014932.59 |

| Parameter | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|
| Total Annual Carbon Emission (Tonn) | 348.00 | 431.55 | 790.92 | 1095.20 | 1014.93 |
| Average Carbon emission per Departure (Tonn) | 1.82 | 1.73 | 2.26 | 2.42 | 2.91 |

## Annex-2: Regression analysis for Airbus A320

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.999613564 |
| R Square | 0.999227277 |
| Adjusted R Square | 0.998454554 |
| Standard Error | 0.006312141 |
| Observations | 5 |

**ANOVA**

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 2 | 0.103044249 | 0.051522125 | 1293.124499 | 0.000772723 |
| Residual | 2 | 7.96863E-05 | 3.98431E-05 | | |
| Total | 4 | 0.103123936 | | | |

**Residual output**

| *Observation* | *Predicted Average Emissions (tons)* | *Residuals* |
|---|---|---|
| 1 | 1.055305358 | 0.00535762 |
| 2 | 1.039863084 | -0.005607035 |
| 3 | 1.286013639 | 0.003357399 |
| 4 | 1.327874139 | -0.002865748 |
| 5 | 1.385774934 | -0.000242236 |

## Annex-3: Regression analysis for Airbus A330

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.999722987 |
| R Square | 0.999446051 |
| Adjusted R Square | 0.998892102 |
| Standard Error | 0.014090088 |
| Observations | 5 |

**ANOVA**

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 2 | 0.716385897 | 0.358192948 | 1804.220442 | 0.000553949 |
| Residual | 2 | 0.000397061 | 0.000198531 | | |
| Total | 4 | 0.716782958 | | | |

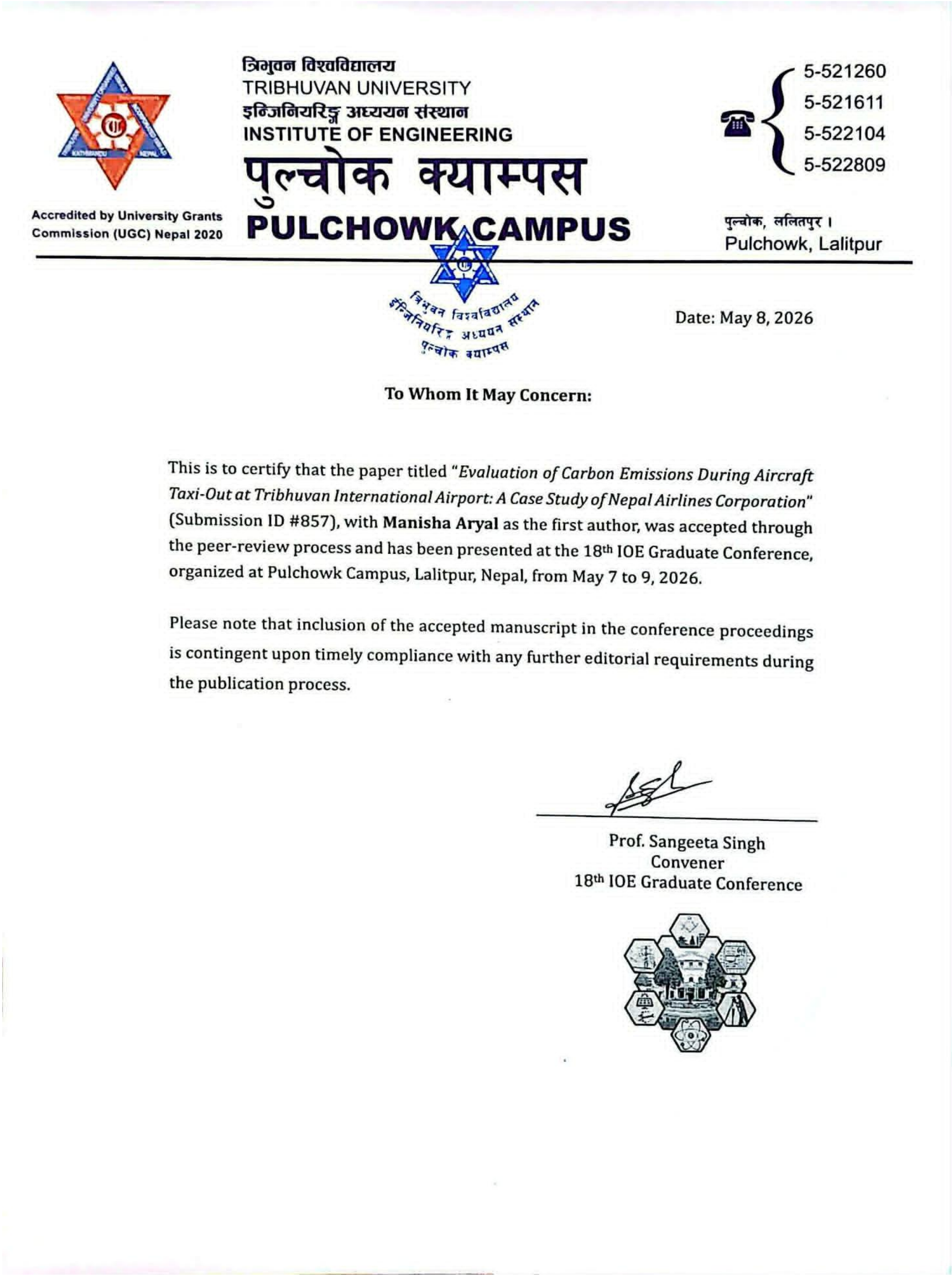
**Residual output**

| *Observation* | *Predicted Average Emissions (tons)* | *Residuals* |
|---|---|---|
| 1 | 1.783833837 | -0.009448695 |
| 2 | 1.81414961 | 0.012188478 |
| 3 | 2.302045204 | -0.01035453 |
| 4 | 2.420321493 | 0.007199707 |
| 5 | 2.780865952 | 0.000415039 |

### Annex-4: Specifications of electric vs diesel tow vehicles

| **Parameter** | **Diesel Aircraft Tug** | **Electric Aircraft Tug** |
|---|---|---|
| Engine / Motor Type | Cummins QSB4.5 Diesel Engine | Permanent Magnet Synchronous Motor (PMSM) |
| Rated Power | 82 kW (110 hp) @ 2500 rpm | 60 kW |
| Emission Standard | Tier III | Zero tailpipe emission |
| Maximum Towing Capacity | Not specified | 150,000 kg |
| Maximum Driving Speed | ~26 km/h | Not specified |
| Torque | Not specified | 350 Nm |
| Rated Speed | Not specified | 1637 rpm |
| Battery Capacity | Not applicable | 124.88 kWh |
| Battery Voltage | Not applicable | 618.24 V |
| Charging Time | Not applicable | 1–1.5 hours (120 kW charger) |
| Operational Range | Not applicable | ~115 km per full charge |

## Annex-5: Paper acceptance letter



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**To Whom It May Concern:**

This is to certify that the paper titled "*Evaluation of Carbon Emissions During Aircraft Taxi-Out at Tribhuvan International Airport: A Case Study of Nepal Airlines Corporation*" (Submission ID #857), with **Manisha Aryal** as the first author, was accepted through the peer-review process and has been presented at the 18th IOE Graduate Conference, organized at Pulchowk Campus, Lalitpur, Nepal, from May 7 to 9, 2026.

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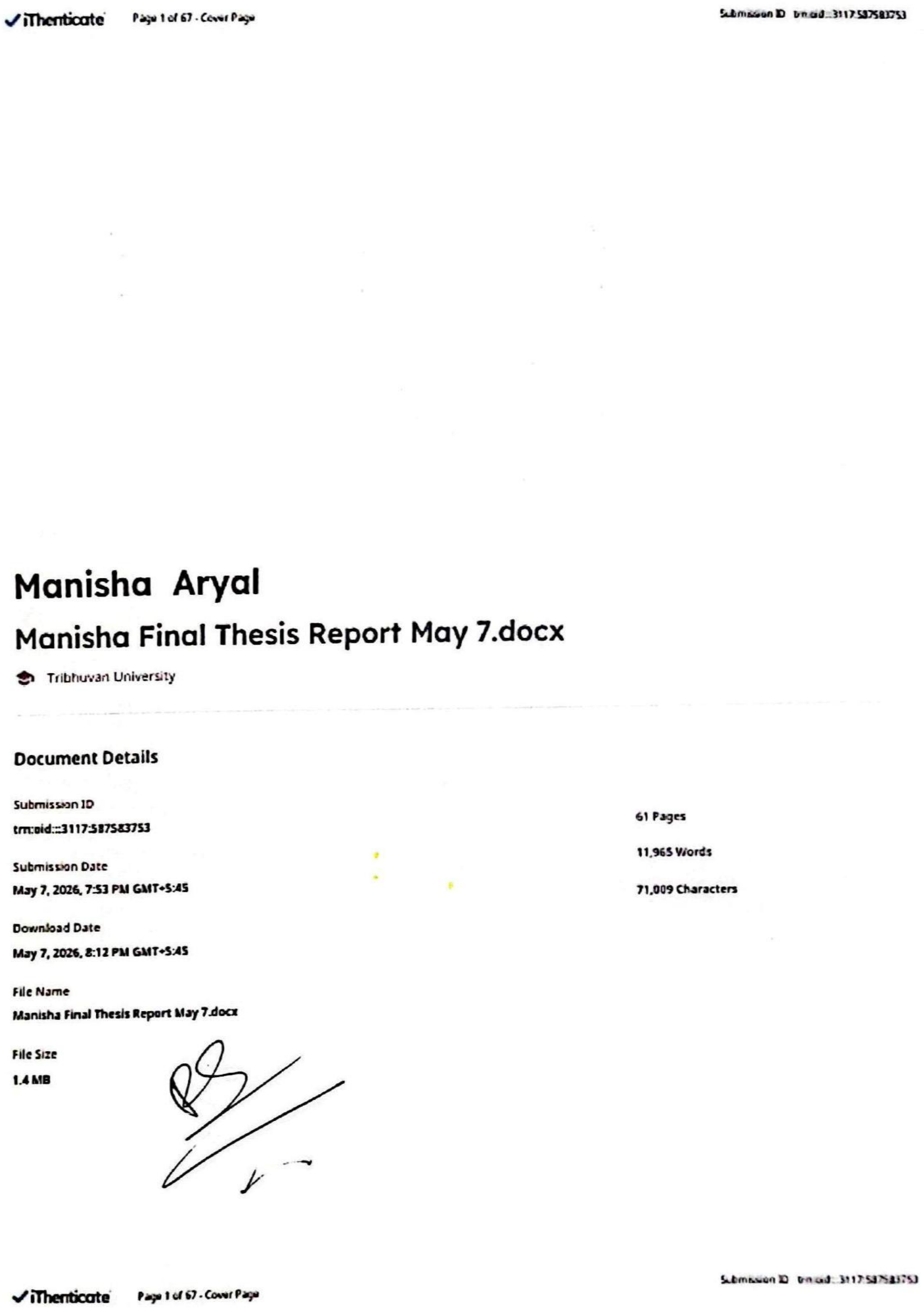

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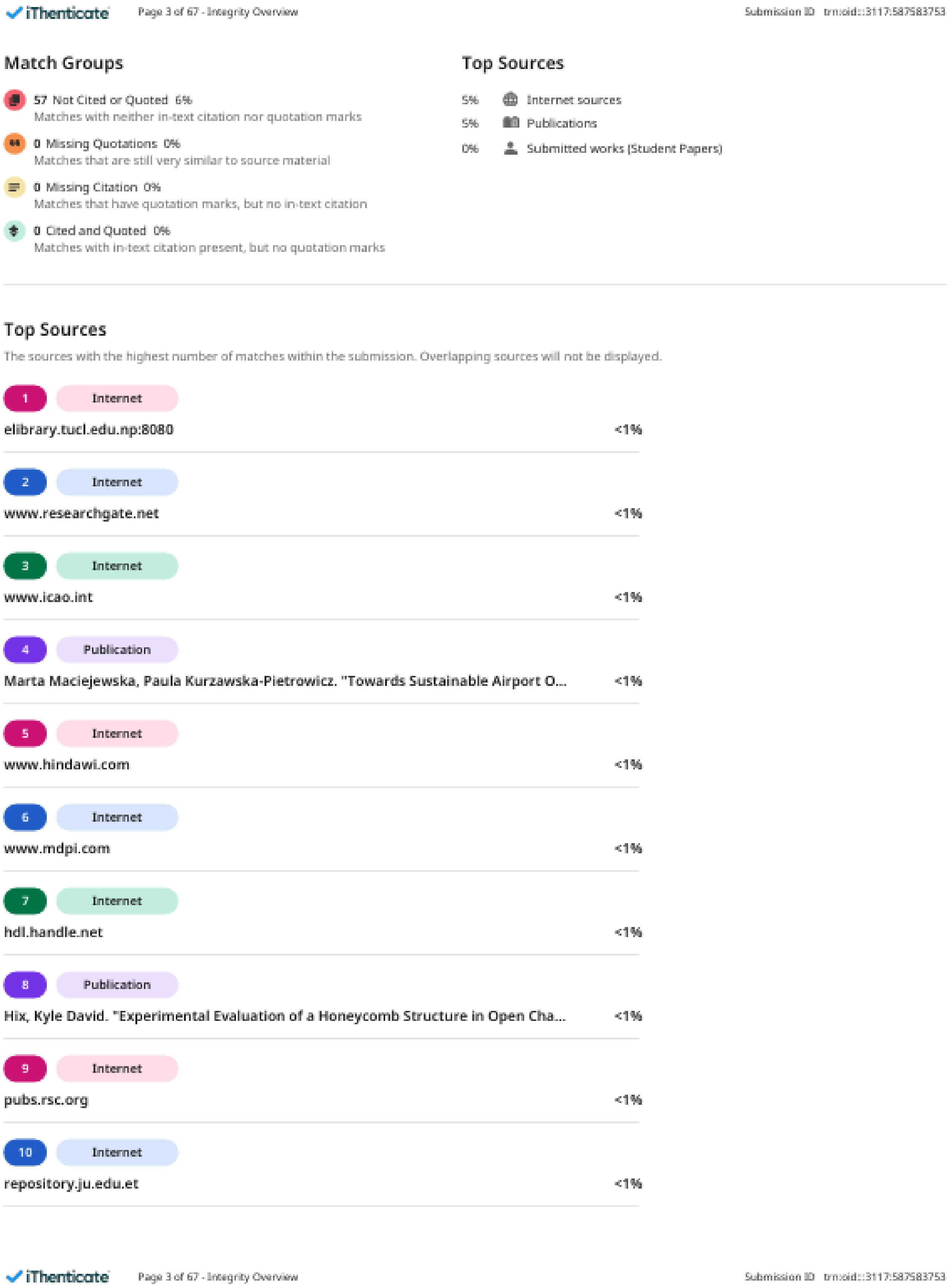

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