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Bottom-up Estimation of GHG Emissions from Philippine Domestic Air Transportation

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Abstract: Many studies, including the Philippine Greenhouse Gas Inventory of the Climate Change Commission, quantify the emissions generated by the air transportation sector using a top-down approach with readily available data on the overall fuel supply. On the other hand, while a bottom-up approach gives a sectoral overview of GHG emissions sources, the lack of extensive activity data proves to be a significant setback in using a bottom-up approach. Using secondary aircraft movement data, emission factors from EMEP/EEA Air Pollutant Guidebook 2019, and estimated cruising distances, this study attempts to provide bottom-up estimates of GHG emissions from the Philippine domestic air transportation between 2010 to 2019. The resulting trends show that the number of trips, aircraft type, and engine type influences the generation of GHG emissions from aircraft operations. The study recommends localizing the inputs for the model to help improve the accuracy of the estimates of the GHG emissions.

Keywords: Air Transportation, GHG Emissions, Bottom-up Estimate, GHG Inventory, Sustainable Transportation

1. INTRODUCTION

In the 2019 Key Energy Statistics, the Department of Energy (DOE) (2020) reports that the greenhouse gases (GHG) emissions of the transportation sector range from 22.7 to 35.5 million tons of carbon dioxide equivalent (MTCO$_2$e) from 2009 to 2019. In the same period, the average annual growth rate of GHG emissions of the transportation sector is 4.6% while, the average annual share of the transportation sector to the total GHG emissions is 29.9%. Figure 1 shows the GHG emissions inventory of the DOE for the energy sector from 2009 to 2019.

Under the transportation sector, the Climate Change Commission (CCC) (n.d.) reports that the GHG emissions from domestic air transportation in 1994 reached 0.606 MTCO$_2$e, which accounts for 3.81% of the total GHG emissions from the transportation sector that year. In the 2000 GHG inventory, the GHG emissions from air transportation increased to 1.02 MTCO$_2$e, which is 3.93% of the total GHG emissions from the transportation sector. The CCC (n.d.) reports in the 2010 GHG inventory that the air transportation GHG emissions decline to 0.712 MTCO$_2$e or 2.95% of the total transportation GHG emissions. Meanwhile, the road transportation subsector contributes the most to the overall GHG emissions from the transportation sector, as seen in Figure 2.

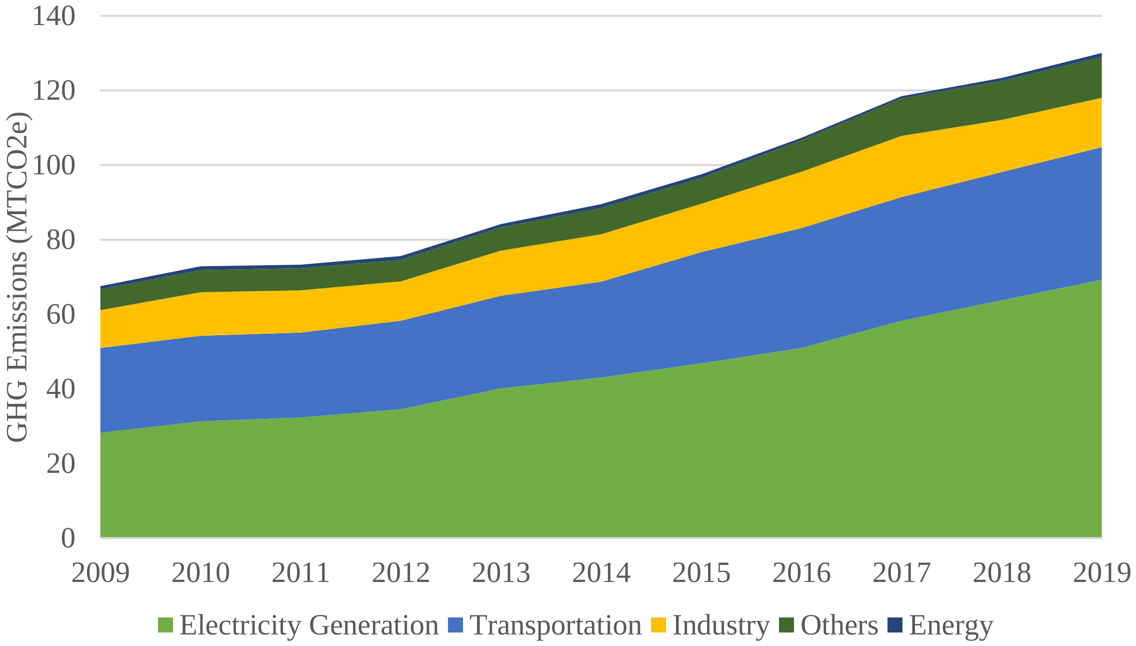

Figure 1. GHG emissions inventory for the energy sector (DOE, 2018)

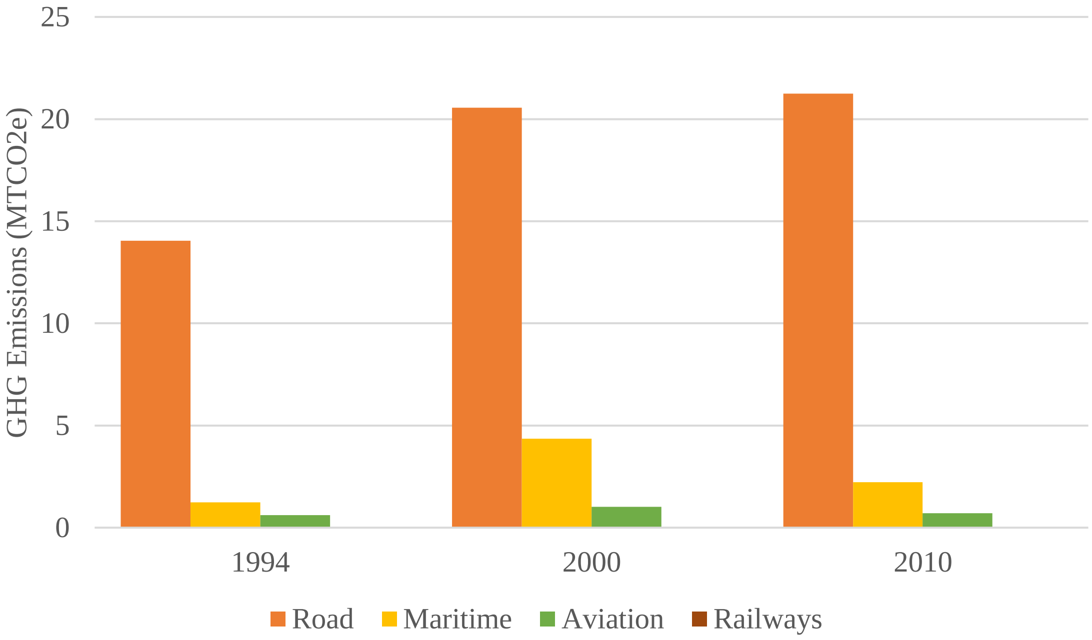

Figure 2. GHG inventory of the transportation sector (Climate Change Commission, n.d.)

In terms of global emissions, the combustion of around 363 billion liters of jet fuel globally in 2019 generated 914 million tons of CO_2 – approximately 2% of all human-induced CO2 that year, according to the Air Transport Action Group (2020). The International Civil Aviation Organization (ICAO) (2010) reports that the air transportation sector contributes 12% of the total CO_2 emissions from the transportation sector. The International Panel on Climate Change (IPCC) (2006) states that jet fuel[1] and aviation gasoline combustion produce CO_2, water

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[1] Jet fuel includes jet kerosene and jet gasoline (IPCC, 2006)

vapor (H_2O), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_x), non-methane volatile organic compounds (NMVOC), and particulates. The ICAO (2010) claims that CO_2 and non-CO_2 emissions impact the climate directly or indirectly depending on their atmospheric lifetime and altitude. The ICAO (2010) emphasizes the effects of CO_2 emissions and their relatively long atmospheric lifetime as the IPCC (2006) describes that approximately 70% of the total GHG emissions from the air transportation sector is CO_2. Therefore, it is significant to estimate the GHG emissions of the air transportation sector to aid the policymakers in formulating comprehensive policies to mitigate the effects of GHG emissions.

The Environmental Management Bureau (EMB) (2011) explains that there are two methods in estimating emissions – the reference or top-down approach and the sectoral or bottom-up approach. According to the EMB (2011), the top-down approach utilizes the overall inventory of fuel supply to estimate GHG emissions, while the bottom-up approach estimates GHG emissions from the actual activities of particular subsectors. The bottom-up approach gives a more comprehensive estimate of GHG emissions because it can detail the sources of emissions under a specific energy sector. However, the EMB (2011) claims that the bottom-up approach relies heavily on extensive activity data – a persistent difficulty in the DOE. The EMB (2011) then suggests that performing both methods will result in a more thorough analysis of GHG emissions. With this, appropriate policies can be formulated and implemented towards the activities which generate more emissions.

Although some local studies attempted to estimate GHG emissions from the air transportation sector, a few utilized the bottom-up approach. The CCC (n.d.), which compiles all the GHG inventories of different sectors, utilizes a top-down approach in their GHG inventories. Moreover, the latest national GHG inventory conducted was for the year 2010. The study can contribute to the limited local literature on the estimation of air transportation GHG emissions and explore an applicable method based on the available data. Hence, the study aims to estimate the GHG emissions from the air transportation sector from 2010 to 2019 using a bottom-up approach. The study will also identify the factors affecting the domestic air transportation GHG emissions from 2010 to 2019 based on the methodology applied.

2. REVIEW OF RELATED STUDIES

2.1 2006 IPCC Guidelines

The IPCC (2006) establishes that the emissions from the air transportation sector cover international and domestic civil aviation as well as landings and take-offs, under the Mobile Combustion category. The IPCC (2006) also includes scheduled passenger and freight flights, general aviation, and air taxiing under the Mobile Combustion category. Meanwhile, the IPCC (2006) excludes emissions from stationary combustion as they put them under the Stationary Combustion category of their guidelines. To split domestic air transportation from international, the IPCC (2006) declares that domestic aviation covers flights that depart and arrives in the same country. In the 2006 IPCC Guidelines, the IPCC (2006) categorizes aircraft operations into landing/take-off (LTO) cycle and cruise. According to the IPCC (2006), aircraft operations at higher altitudes generate around 90% of aircraft engine emissions, while the remaining 10% of aircraft engine emissions (excluding CO and hydrocarbons) come from LTO cycles and ground operations. The IPCC (2006) states that emissions depend on the following: (1) frequency of different types of aircraft operations; (2) fuel consumption during the said operations; (3) flight distance and altitude; (4) duration per flight phase; and (5) aircraft engine specifications.

The IPCC (2006) proposes a three-tiered approach for estimation emissions from the air transportation sector. Tier 1 requires fuel consumption data, specifically aviation gasoline and jet fuel consumption. From the consolidated fuel consumption data, emissions are computed by multiplying average emission factors. The IPCC (2006) assigns an emission factor based on fuel type – aviation gasoline and jet fuel. The Tier 1 approach also assumes one emission factor for non-CO_2 emissions (CH_4, nitrous oxide (N_2O), and NO_x) for all aircraft types. The IPCC (2006) suggests using the Tier 1 approach to estimate emissions from the combustion of aviation gasoline, which is less than 1% of the fuel consumption of the air transportation sector. For other aircraft operations, the IPCC (2006) advises to use the Tier 2 or Tier 3 approach and only use Tier 1 if data on aircraft operations are not available. As Tier 1 is entirely fuel-based, it may not characterize the individual sources of emissions. The IPCC (2006) recommends the Tier 2 and Tier 3 methods to distinguish source categories more accurately. Furthermore, Tier 2 and Tier 3 can reflect the effects of advancements in aviation technologies in the future.

For Tier 2, the IPCC (2006) requires data on jet fuel consumption and the number of LTO cycles per aircraft type. Moreover, Tier 2 requires information on fuel consumption during LTO to characterize emissions from LTO and cruise flight phases. Tier 2 considers emissions generated under 914 m (3000 ft) as LTO emissions, while emissions above 914 m (3000 ft) are from the cruise phase. The IPCC (2006) estimates emissions in the LTO phase using the frequency of LTO cycles, LTO fuel consumption factors, and emission factors per aircraft type. The IPCC (2006) provides a range of typical aircraft types with their corresponding LTO emission factors (CO_2, CH_4, N_2O, NO_x, CO, NMVOC, and SO_2) and fuel consumption. Tier 2 estimates the fuel consumption during the cruise phase by subtracting the fuel consumption during LTO from the total fuel consumption. Then, emissions are computed accordingly using emission factors per fuel type used in Tier 1. For a more comprehensive Tier 2 estimation, the IPCC (2006) recommends acquiring LTO data on frequently used aircraft types because Tier 2 might exclude general aviation flights non-scheduled flights.

Depending on the complexity of the available movement data, the IPCC (2006) advises using Tier 3A or Tier 3B. Tier 3A requires flight data on origin and destination per aircraft type, while Tier 3B requires complete flight trajectory data for complex modeling. Instead of deriving the fuel consumption of the cruise phase from the LTO and total fuel consumption, Tier 3 methods generate a more accurate estimation of emissions from the cruise phase. Tier 3A estimates emissions in the LTO phase using average fuel consumption and emissions factors per aircraft type. For the cruise phase, Tier 3A recognizes the effect of flight distance on fuel consumption such that fuel consumption rate can be relatively higher on shorter distances than on longer paths. Thus, the fuel consumption rate during the LTO phase is higher than during the cruise phase. Tier 3B calculates emissions from each flight segment of the flight trajectory using sophisticated modeling tools accounting data on aircraft and engine performance. Even though Tier 3B requires the most intensive resources, Tier 3B can provide a wide range of output while considering aircraft equipment developments and air traffic. According to the IPCC (2006), Tier 3B is also adaptive to advancing aircraft operations systems, thus generating the most updated estimation among the other tiers.

2.2 Philippine Greenhouse Gas Inventory Studies

The Philippine Government (2014) passed Executive Order No. 174 (2014) to institutionalize the Philippine Greenhouse Gas Inventory Management and Reporting System (PGHGIMRS), which assigns the Climate Change Commission (CCC) as the lead agency in the collection and reporting of GHG inventories in all key sectors. Meanwhile, the Department of Transportation (DOTR) is mandated to lead the transportation sector to conduct, monitor, and report its GHG inventory. In the 2010 Philippine Greenhouse Gas Inventory Report, the CCC (n.d.) states that the methodologies applied are under the 2006 IPCC Guidelines. For the 2010 GHG inventory, the CCC (n.d.) utilized the Tier 1 method to estimate CO_2, CH_4, N_2O, and hydrofluorocarbons (HFCs) emissions. The CCC (n.d.) expresses nonCO_2 emissions in $MTCO_2e$ using global warming potential (GWP) values of the IPCC. The CCC (n.d.) reports that in 2010, the GHG emissions from domestic air transportation is 0.712 $MTCO_2e$, of which more than 99% is CO2, and the remaining is N_2O.

The EMB (2011) published an inventory manual on tracking GHG emissions for government agencies and private sectors to generate GHG emissions data from the five main economic sectors – energy, industry, agriculture, land-use change and forestry, and waste. The EMB (2011) provides guidelines of the estimation process using the United Nations Framework Convention on Climate Change (UNFCCC) software for the five main economic sectors. The UNFCCC software is a spreadsheet-based program that serves as a tool to develop national GHG inventories. The EMB (2011) outlines the process of estimation using the UNFCCC software through a top-down and bottom-up approach. The EMB (2011) also includes the consolidation of GHG inventories from the subsectors of each of the main economic sectors. Furthermore, the EMB (2011) gives the equivalent IPCC fuel categories of the fuel classifications set by the UNFCCC to input the proper IPCC emission factor.

The Asian Development Bank (ADB) (2016) published guidelines for GHG estimations for their projects on the transportation sector of the Philippines. The ADB (2016) suggests three methods parallel to the three tiers of the IPCC to estimate GHG emissions depending on the complexity of the available data. The ADB (2016) also recommends considering emissions from the construction and operations of airports. For non-CO_2 emissions, the ADB (2016) advises including the combination of CO_2 with NO_x, contrails, and cirrus clouds, which generates up to five times GWP than CO_2 only. The ADB (2016) suggests tools developed by international organizations such as the ICAO Carbon Emissions Calculator and the Guidebook on Preparing Airport Greenhouse Gas Emissions Inventories by the United States Federal Aviation Administration.

Baal and Fulgencio (2019) estimated CO_2, N_2O, and CH_4 emissions from the Philippines' domestic air transportation for 2014 using a bottom-up approach. For the emissions during the LTO phase, Baal and Fulgencio (2019) assume aviation gasoline for the fuel consumption of all flights. Baal and Fulgencio (2019) only estimated CO2 and N2O emissions for the cruise phase because CH_4 emissions are negligible at cruise altitudes. Baal and Fulgencio (2019) report that CO2, N_2O, and CH_4 emissions in 2014 are 3200 kilotonnes, 11 kilotonnes, and 690 kilotonnes, respectively. This bottom-up estimate covers domestic flights across 33 airports in the country. Baal and Fulgencio (2019) also attempted to estimate emissions using fuel sales data following the Tier 1 methodology of the IPCC. Baal and Fulgencio (2019) report considerably lower GHG emissions using the Tier 1 approach than the bottom-up estimate because of the differences in the actual and estimated cruising distance used in the calculations.

2.3 Other GHG Estimation Guidelines

The ICAO (2018) established the ICAO Carbon Emissions Calculator for estimating CO_2 emissions based on the flight distance and aircraft type. The ICAO (2018) requires data on origin-destination pairs, fuel consumption factors, passenger load factors, and the number of economy seats for their emissions calculator. The ICAO (2018) uses the great circle distance (GCD) to approximate the flight distance between origin and destination pairs. The ICAO (2018) applies correction factors in Table 1 to the GCD for a more accurate flight distance estimation. The ICAO (2018) sets 3.16 as the CO_2 emission factor per ton of combusted aviation fuel.

Table 1. GCD correction factors (ICAO, 2018)

GCD	Correction to GCD
Less than 550 km	+50 km
Between 550 km and 5500 km	+100 km
Above 5500 km	+125 km

The European Environment Agency (EEA) (2019) published the EMEP/EEA Air Pollutant Emission Inventory Guidebook, which outlines methodologies in the estimation of air pollutants such as CO_2, NO_x, CH_4, and particulate matter (PM), from different sources like air transportation. The EEA (2019) advises obtaining and analyzing both top-down and bottom-up data from government agencies, airport authorities, and actual surveys on aircraft movement. The EEA (2019) divides aircraft operations into the LTO phase and climb-cruise-descent (CCD) stage. Parallel to the IPCC Guidelines, the EEA (2019) recommends three methodologies in estimating GHG emissions. For Tier 1, the EEA (2019) requires information on total fuel sales and the frequency of LTO and CCD cycles. While both Tier 1 of the 2006 IPCC Guidelines and the EEA (2019) estimate the GHG emissions using only one representative aircraft type for Tier 1, the Tier 1 of the EEA can characterize emissions from the LTO and CCD phase in contrast to the Tier 1 of the 2006 IPCC Guidelines. Tier 2 of the EEA (2019) requires information on fuel sales data and the number of LTO and CCD cycles. Tier 2 also involves information on aircraft types used because estimating GHG emissions for the LTO phase depends on the aircraft type. The EEA (2019) provides an accompanying spreadsheet for the detailed LTO GHG emissions estimation. Still, Tier 2 estimates GHG emissions in the CCD phase using one representative aircraft type only. The Tier 3 methodology is analogous to the Tier 3 of the 2006 IPCC Guidelines. For Tier 3A, the EEA (2019) provides an accompanying spreadsheet with fuel consumption rates and GHG emission factors for a wide range of aircraft types. This calculation tool can generate GHG emissions from a flight with details on aircraft type and cruise distance. The GHG emissions of each flight can be compiled to produce a GHG inventory from aircraft operations.

The EEA (2019) adapted the EUROCONTROL fuel burn and emissions system (FEIS) in their accompanying spreadsheets for the EMEP/EEA Air Pollutant Guidebook. According to the EEA (2019), EUROCONTROL derived the FEIS from the ICAO Aircraft Engine Emissions Databank for fuel consumption rates and emission factors for NO_x, unburned hydrocarbons (UHC), and CO during the LTO phase. For NO_x, UHC, and CO emissions during the CCD phase, EUROCONTROL used their database, Base of Aircraft Data (BADA), and the Boeing Fuel Flow Method 2 (BFFM2). Moreover, the FEIS estimates CO_2, H_2O, and SO_x emissions relative to the fuel consumption during the LTO and CCD phases. The FEIS estimates the volatile organic compounds (VOCs) emissions from the amount of UHC emitted. The EUROCONTROL uses the most common type of engine in 2015 in their FEIS.

3. METHODOLOGY

This study estimates the GHG emissions of the Philippine domestic air transportation sector using a methodology parallel to the Tier 3A methodology, a bottom-up approach, of the 2006 IPCC Guidelines and the EMEP/EEA Air Pollutant Emission Guidebook 2019. The estimation covers the GHG emissions of domestic flights, as defined by the IPCC (2006), from 2010 to 2019. The emissions to be estimated include CO_2, NO_x, SO_x, H_2O, CO, hydrocarbons (HC), non-volatile PM, and volatile PM (organic and sulfurous).

3.1 Calculation Framework

The calculations are executed using a spreadsheet software following the flowchart in Figure 3 and Equation 1. The calculations are disaggregated into the computation of emissions during the LTO and CCD phases. In the LTO phase, the GHG emissions are estimated per flight based on the ICAO default LTO cycle. In the CCD phase, the GHG emissions are computed from an array of values depending on the cruising distance of a flight. The total emission per pollutant is the sum of emissions in the LTO and CCD phases.

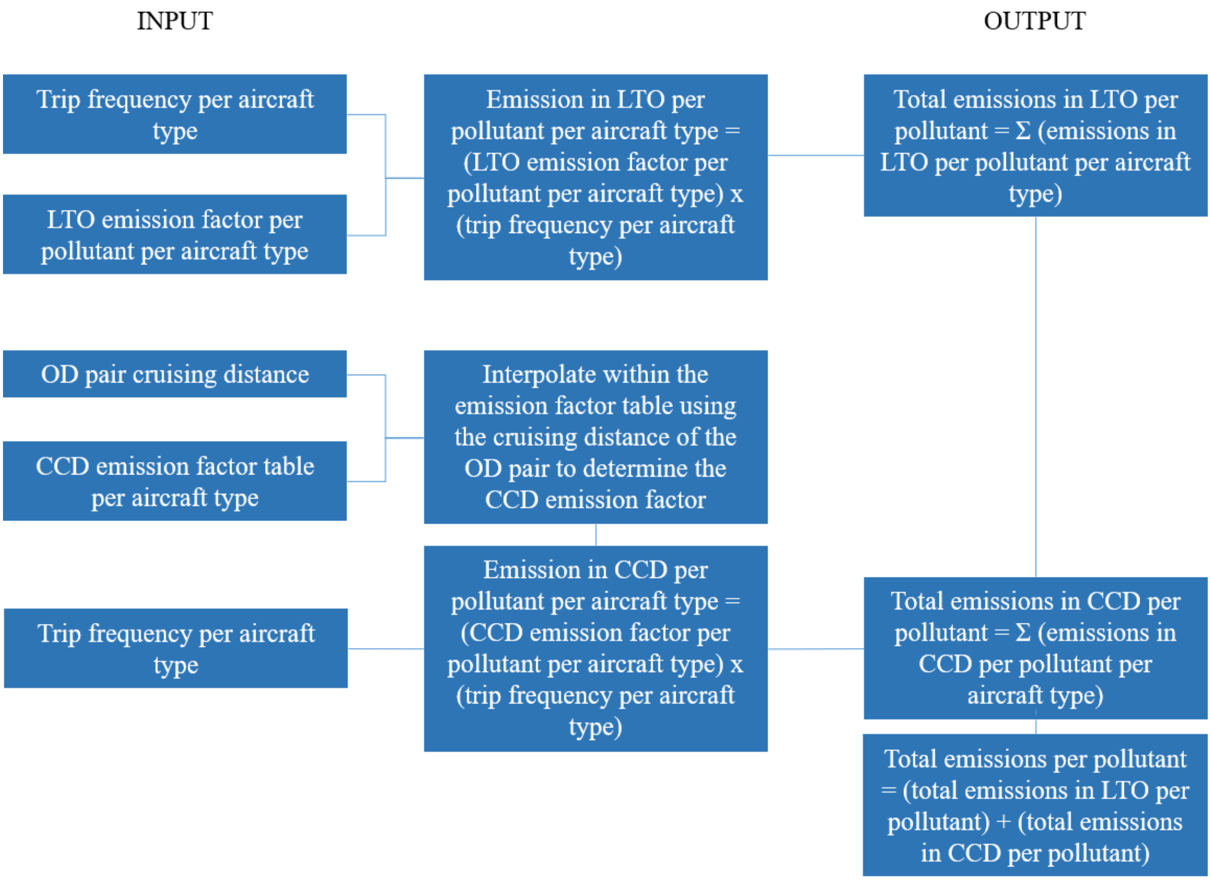

Figure 3. Calculation framework for estimation of GHG emissions

$$EM_{pollutant,i} = \sum_{j} \sum_{k} \left(EF_{pollutant,LTO,k} \times TF_{j,k}\right) + \left(EF_{pollutant,CCD,k} \times TF_{j,k}\right) \quad (1)$$

where,

i : year,
$pollutant$: type of pollutant,
$EM_{pollutant,i}$: emission (kg) of $pollutant$ for year i,
j : origin and destination (OD) pair,
k : aircraft type,
$EF_{pollutant,LTO,k}$: LTO emission factor of $pollutant$ for aircraft type k (kg),
$TF_{j,k}$: trip frequency for OD pair j of aircraft type k, and
$EF_{pollutant,CCD,k}$: CCD emission factor of $pollutant$ for aircraft type k (kg).

3.2 Data requirements

3.2.1 Aircraft movement data

Aircraft movement data sourced from a private data provider covers scheduled domestic flights from 2010 to 2019. Details on origin and destination airports, trip frequency, and aircraft type are available on the aircraft movement data. As prescribed by the IPCC (2006), information on the origin and destination of flights is the main data requirement for the Tier 3A method. Other aircraft operations such as general aviation and military aircraft operations are not included in the database. Thus, the estimation only covers the flights included in the aircraft movement data.

3.2.2 Emission factors

The accompanying spreadsheet of the EMEP/EEA Air Pollutant Emission Guidebook 2019 provides emission factors for the LTO and CCD phase of a flight for a wide range of aircraft types. The emission factors of the aircraft types included in the aircraft movement data are extracted from the said spreadsheet. For emissions during the LTO phase, the emission factor depends only on the aircraft type. The emission factors during the LTO are based on the ICAO default LTO cycle which is 32 minutes and 54 seconds. On the other hand, emissions during the CCD phase depend on the aircraft type and the cruising distance. The methodology applied uses interpolation within a table of emission factors depending on the cruising distance of an OD pair for the CCD phase.

3.2.3 Cruising distance

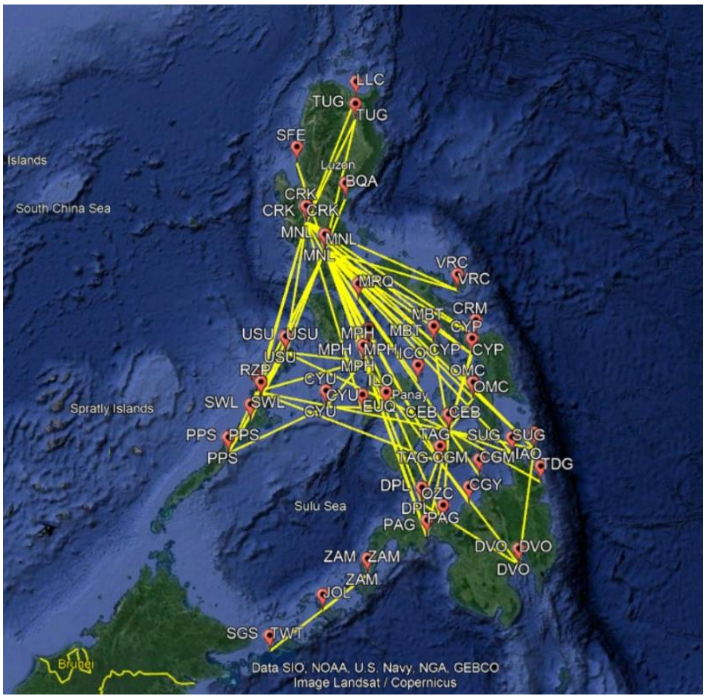

Figure 4. Cruising distance estimation with Google Earth Pro (Google Earth Pro, n.d.)

The methodology estimates the cruising distance using the Philippine En-route Chart from the Civil Aviation Authority of the Philippines (CAAP). The cruising distance considered in the estimation is the shortest series of air traffic service (ATS) routes per origin and destination (OD) pair. However, some airports do not have ATS routes connecting them to other airports. To address this gap, their cruising distance is estimated using the scale of the Philippine En-route Chart. Furthermore, some airports are not visible on the Philippine En-route Chart. A geographic information system (GIS) software, Google Earth Pro, is used to estimate the cruising distance of OD pairs involving the said airports. The methodology applies correction factors in Table 1 by the ICAO (2018) to increase the accuracy of the estimated cruising distance.

4. RESULTS AND DISCUSSIONS

The results show that estimated CO_2 emissions from the domestic air transportation sector range from 1.2 to 1.9 megatonnes (MT) from 2010 to 2019, with an average annual growth rate of 5.2%. The average annual share of CO_2 emissions from the LTO and CCD phases are 28% and 72%, respectively. Figure 5 displays the trend of CO_2 emissions from 2010 to 2019. The Environmental and Energy Study Institute (EESI) (2019) states that 30% of CO_2 emissions is naturally eliminated from the atmosphere after being generated. Then, approximately 50% of the produced CO_2 stays in the atmosphere within hundreds of years while the 20% remains for thousands of years. The CAAP (2018) submitted the Philippines ' Action Plan on CO_2 Emission Reduction to the ICAO to decrease air transportation emissions. The CAAP (2018) establishes its strategies to reduce emissions from the air transportation sector by improving the fuel efficiency of the country's fleet annually by 2% starting 2020. The CAAP (2018) proposes implementing aircraft and engine technology improvements, airport ground operations, and air traffic management.

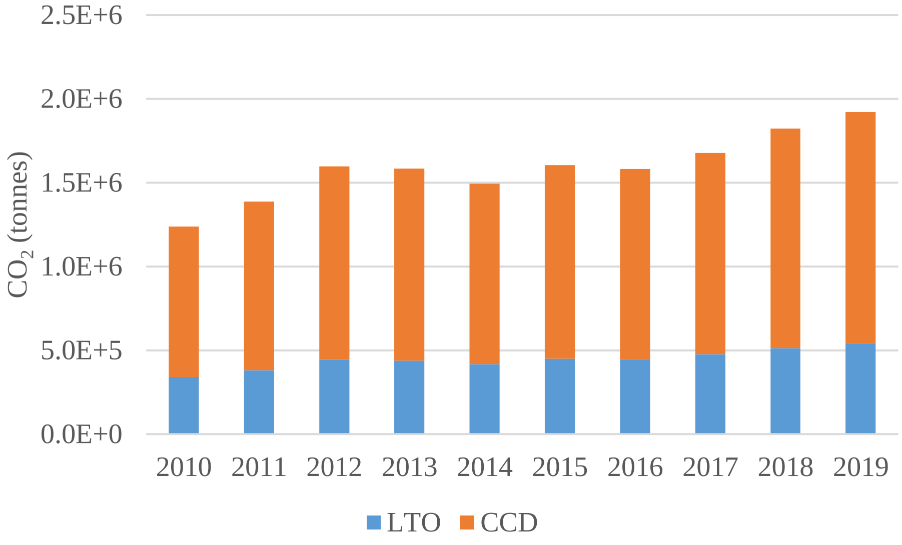

Figure 5. CO_2 emissions from 2010 to 2019

Estimated CO_2, H_2O, and SO_x emissions have the same average annual growth rate and shares of emissions from the LTO and CCD phases because their emission factors are relative to the fuel consumption. Also, estimated CO_2, H_2O, and SO_x peaked during 2019, when the most number of domestic trips are recorded. H_2O emissions vary from 480 to 750 kilotonnes from 2010 to 2019 while SO_x emissions range from 330 to 510 tonnes in the same period. The EESI (2019) describes that aircraft operations produce water vapor in condensation trails or contrails that trap infrared rays resulting in thrice the warming impact of CO_2. The ICAO (2016) explains that SO_x emissions generate secondary PM by reacting with ammonia (NH_3) and further deposits to the Earth's surface affecting the air quality. Figures 9 and 10 in Appendix A show the annual H_2O and SO_x emissions, respectively.

NO_x emissions from 2010 to 2019 follow a closely similar trend to the estimated CO_2, H_2O, and SO_x emissions in the same period, as seen in Figure 11 in Appendix A. NO_x emissions range from 6 to 10 kilotonnes for the years 2010 to 2019 with an average annual growth rate of 6.1%. On average, 23.6% of the total NO_x emissions come from the LTO phases, while the remaining 76.4% is from the CCD phase. According to the ICAO (2016), NH_3 and NO_x emissions reactions generate PM and affect the air quality on the Earth's surface. Moreover, the US Federal Aviation Administration (FAA) (2015) states that NO_x emissions remove CH_4 from the atmosphere but have a net warming effect because of the generation of ozone (O_3) gases.

CO and HC emissions peaked in 2012, unlike the other emissions, which peaked in 2019. In 2012, estimated CO emissions reached around 2.6 kilotonnes, as shown in Figure 6, while HC emissions peak at 540 tonnes. From 2010 to 2019, CO emissions range from 2.3 to 2.6 kilotonnes with an average growth rate of 1.5%. Around 57.8% of the total emissions are from the LTO phase, while 42.2% originate from the CCD phase. As illustrated in Figure 12 in Appendix A, HC emissions vary from 400 to 540 tonnes in the same period, with an average annual growth rate of -2.2%. The LTO phase of domestic trips from 2010 to 2019 generates 59.3% of the total HC emissions, while the CCD phase produces 40.7%. The US FAA (2015) explains that aircraft engines generate HC and CO emissions because of incomplete fuel combustion during ground operations. This explains why the majority of CO and HC emissions come from the LTO phase. Indeed, the extracted CO and HC emission factors show that emissions during the LTO phase are relatively higher than emissions during the CCD phase with a cruising distance lower than 250 nautical miles.

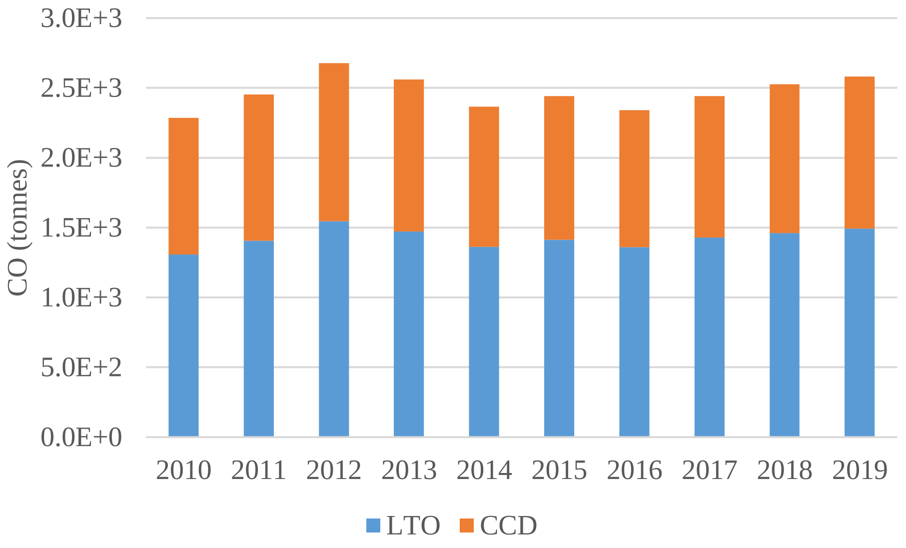

Figure 6. CO emissions from 2010 to 2019

Total non-volatile PM emissions from 2010 to 2019 are 6 to 30 tonnes, with an average annual growth rate of 18.8%, as seen in Figure 7. On average, 17.4% of the total non-volatile emissions came from the LTO phase, while 82.6% from the CCD phase. From 2014 to 2015, the annual growth rate reaches more than 100% which is mainly attributed by the increase in the trips made by Airbus 321 in 2015. The continuous increase in the frequency of Airbus 321 trips until 2019 contributes to the growth of non-volatile PM emissions. Some aircraft types, including Airbus 321, have greater non-volatile PM emission factors than volatile PM emission factors. Also, PM emission factors for turboprop-engined aircraft types are not available in EMEP/EEA Guidebook thus, not considered in the estimation.

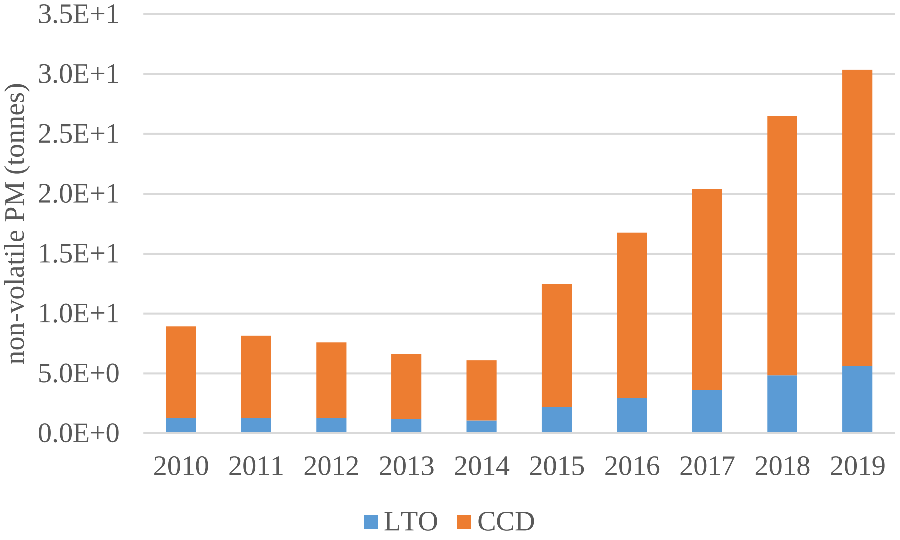

Figure 7. Non-volatile PM emissions from 2010 to 2019

On the other hand, the total volatile PM emissions from 2010 to 2019 range from 30 to 50 tonnes with an average annual growth rate of 5.3% as shown in Figure 13 in Appendix A. On average, 21.2% of the total volatile PM emissions is from the LTO phase, while 78.8% is from the CCD phase. The trend of volatile PM emissions from 2010 to 2019 follows the same behavior of the CO_2 emissions in the same period. Some aircraft types such as Airbus 319, Airbus 320, and Boeing 737 have higher volatile PM emission factors than their non-volatile PM emission factors. This can contribute to the behavior of non-volatile emissions from 2010 to 2019. Also, the continuous increase in Airbus 319 trips adds to the growth of volatile PM emissions from 2016 to 2019. The US FAA (2015) asserts that PM emissions can travel very long distances, stay in the atmosphere for weeks, and harm the population's health due to their very small size.

In the bottom-up estimation, the number of trips made by each aircraft is one of the factors affecting the GHG emissions per year. As seen in the figure below, the trend of the annual frequency of trips is similar to the behavior of estimated CO_2, H_2O, SO_x, NO_x, and volatile PM emissions. This follows the fact that the emission factors used in the calculations are based on the fuel consumption calculation methodology of EUROCONTROL. Subsequently, the EEA (2019) states that EUROCONTROL uses aircraft movement data such as cruising distance, and origin and destination airports in estimating fuel consumption. The aircraft and engine type also contribute to the behavior of GHG emissions from 2010 to 2019. Due to engine specifications, GHG emission factors vary from one engine type to another and sometimes override the effect of the number of trips, like in the case of CO and HC emissions.

In terms of global GHG emissions, the computed total CO_2 emissions in 2019, 1.9 million tonnes, is around 0.21% of the total CO_2 emissions of air transportation in 2019. In local settings, the estimated total CO_2 emissions in 2019 of air transportation is approximately 5.41% of the total emissions of the transportation sector.

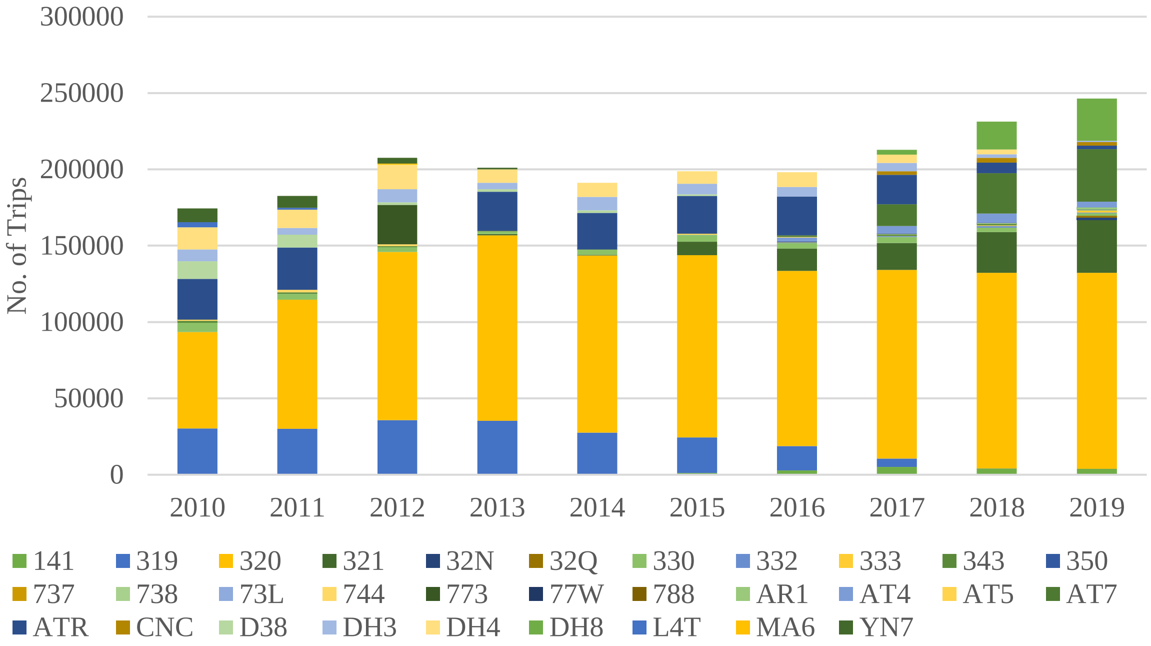

Figure 8. Annual number of trips per aircraft type

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

With the secondary aircraft movement data, extracted emission factors from EMEP/EEA Air Pollutant Guidebook 2019, and estimated cruising distances, this study estimated the CO_2, NO_x, SO_x, H_2O, CO, HC, non-volatile PM, and volatile PM emissions from the Philippine domestic air transportation sector from 2010 to 2019. Tables 2 and 3 in Appendix B summarizes the estimated GHG emissions. The study has also demonstrated using a bottom-up model most suited to the available transportation data. The chosen model can assess the effects of transportation activity and aircraft technology on domestic air transportation emissions.

It was found that the GHG emissions trends within the study period vary according to the number of trips and aircraft and engine types. Limitations of the methodology applied include the estimation of cruising distances, the use of secondary emission factors, and the coverage of obtained aircraft movement data.

5.2 Recommendations

Developing a database for emission factors measured from the local fleet, specific to their engine types, could better establish the GHG emissions from the domestic air transportation sector using a bottom-up approach. Another factor that would enhance the accuracy of the bottom-up estimation is a standardized and more comprehensive approach to measure cruising distances. The interpolation of emission factors during the CCD phase depends on the cruising distance, so developing cruising distances for local aircraft routes would improve the estimates significantly. In the case of the emission factors during the LTO phase, a standard local duration of the LTO cycle could also help to manifest actual conditions during the LTO phase in the domestic air transportation sector. Further studies that evaluate the effects of environmental policies of agencies overseeing the domestic air transport, using the bottom-up model demonstrated in this study, would also be useful. Also, the inclusion of more pollutants in both bottom-up and top-down evaluation of GHG inventory can broaden the perspective on air transportation emissions. Moreover, further exploring the results of this study to come up with future growth rates and comparing these values with the emissions growth rates of other modes of transportation would also be beneficial.

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APPENDICES

APPENDIX A

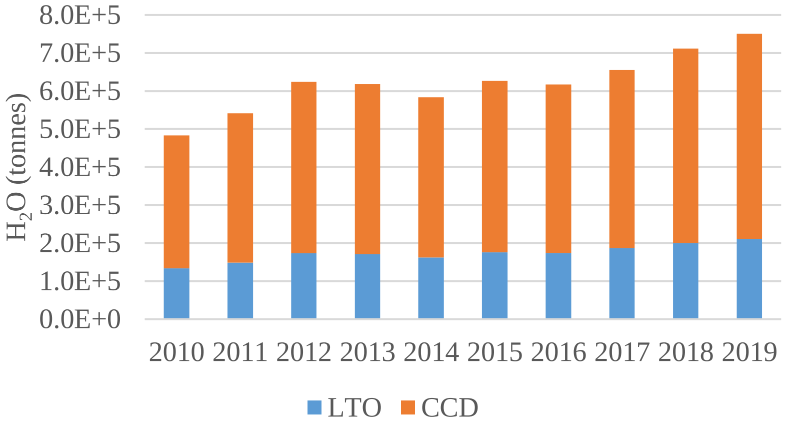

Figure 9. H_2O emissions from 2010 to 2019

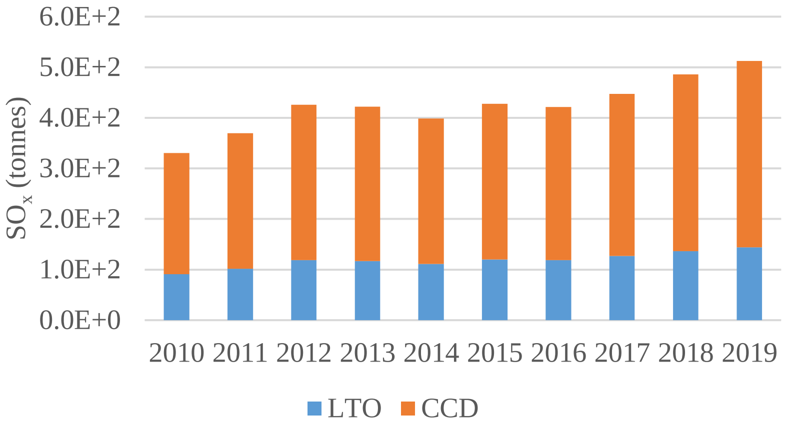

Figure 10. SO$_x$ emissions from 2010 to 2019

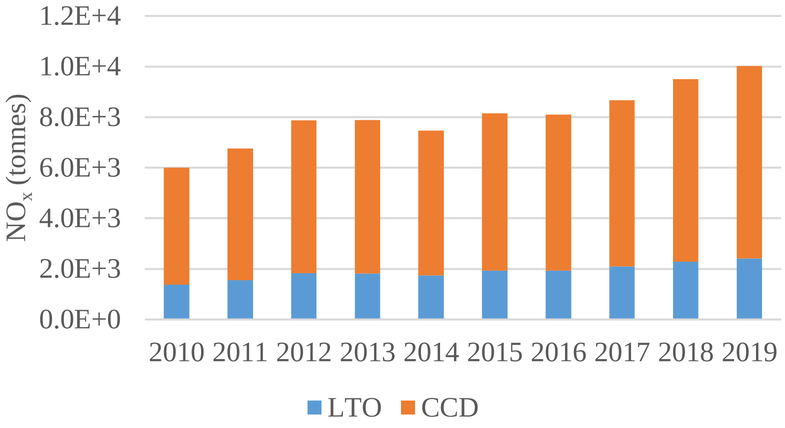

Figure 11. NO$_x$ emissions from 2010 to 2019

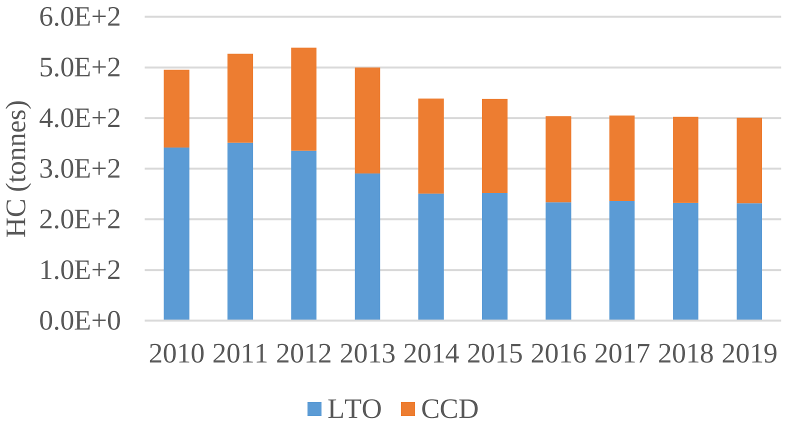

Figure 12. HC emissions from 2010 to 2019

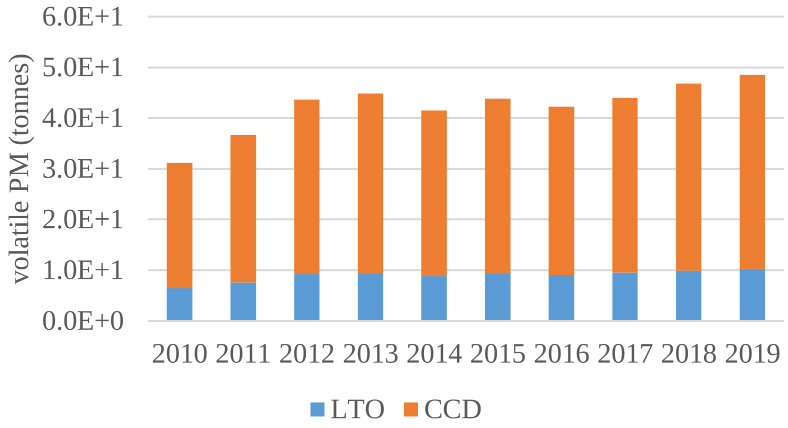

Figure 13. Volatile PM emissions from 2010 to 2019

APPENDIX B

Table 2. Estimated CO_2, NO_x, SO_x, and H_2O emissions from 2010 to 2019

Year	CO_2 (tonnes)	NO_x (tonnes)	SO_x (tonnes)	H_2O (tonnes)
2010	1,238,651.48	5,999.70	330.31	483,663.91
2011	1,387,078.00	6,764.37	369.89	541,620.99
2012	1,597,118.54	7,874.49	425.90	623,636.86
2013	1,583,774.45	7,883.98	422.34	618,426.32
2014	1,494,128.88	7,462.53	398.43	583,421.84
2015	1,604,806.21	8,146.56	427.95	626,638.70
2016	1,581,218.54	8,101.36	421.66	617,428.28
2017	1,678,114.71	8,664.63	447.50	655,263.92
2018	1,822,379.73	9,503.18	485.97	711,596.02
2019	1,922,429.55	10,018.85	512.65	750,663.09

Table 3. Estimated CO, HC, non-volatile PM, volatile PM emissions from 2010 to 2019

Year	CO (tonnes)	HC (tonnes)	Non-volatile PM (tonnes)	Volatile PM (tonnes)
2010	2,286.70	495.57	8.91	31.21
2011	2,451.85	527.05	8.14	36.63
2012	2,676.57	539.23	7.58	43.64
2013	2,560.85	499.73	6.62	44.87
2014	2,364.60	438.53	6.10	41.49
2015	2,440.91	437.97	12.45	43.87
2016	2,340.39	403.93	16.76	42.27
2017	2,441.52	405.04	20.43	44.00
2018	2,527.02	402.70	26.52	46.80
2019	2,580.12	400.52	30.36	48.55

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