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QUANTIFICATION MODEL OF AIRPORT GROUND SUPPORT EQUIPMENT EMISSIONS

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Abstract. Emissions of aircraft support vehicles (called Ground Support Equipment or GSE) are produced by a series of factors depending mostly on the following: aircraft arrivals and departures and time spent in parking stands, aircraft type, operation type (traditional, with scale or low cost), geometrical arrangement of the apron and fleet charactistics, including power and years of use, among others. The aim of this work is to develop an integrated model identifying the required GSEs and the gaseous emissions produced by them due to apron traffic and aircraft service. In order to do this, in the case of service, the model proposes considering loading and unloading and dividing them into the following stages: wait, connection, service and disconnection. The advantage of the proposed model over other proposals is that this model aims at copying the real movements of support vehicles in service according to the aircraft and its corresponding operation (Full-Service, Low-Cost or scale). In order to do that, the program discretizes GSE movements into loading and unloading processes through different stages and for circulation where the tool itself sets the parameters of the apron.

Keywords: sustainable air transport, airport environmental management, airport operations, aviation emissions, quantification model.

Introduction

Aviation in general and air transportation in particular have become an essential part of citizens' lives during the last fifty years. Their positive economic, social and political effects are so clear and have become so essential that it is hard to imagine today's world without aviation. However, aviation generates an adverse ecological impact both on the environment and on the urban environment around airports. Generally, the environmental effects of aviation can be divided into two broad categories (International Civil Aviation Organization [ICAO], 2019b): local effects and global effects.

Local effects are those perceived in areas near airports, in the form of noise, air-quality deterioration, land occupation and local habitat alteration. Even though there has been considerable progress in controlling these effects, they are still the ones causing the greatest number of complaints among affected citizens, particularly the one regarding noise (ICAO, 2002).

Global effects are those that influence general life conditions on planet Earth, such as the use of non-renewable natural resources (mainly oil and some metals), the occupation of air space and radio spectrum band space, and the contribution to global warming which could boost climate change and have a great impact on public opinion. Global effects of aeronautical activity have been the reason for the last two Annexes of Volume 16 (ICAO, 2017, 2019a).

Considering aircraft are not the only source of emissions to take into account when making an inventory (ICAO, 2011), there is a need for a thorough comparative analysis of said sources which has only been globally developed in a few cases and using standard (simple) methodologies (Coppa, 2019; Mokalled et al., 2018). Different authors have carried out specific studies about each of the sources, in which they specifically analyze the contribution of Ground Access Vehicles (Trujillo, 2017; Bukovac & Douglas, 2019; Orth et al., 2015) and GSEs. These will be delved into in this study.

Winther et al. (2015) state that both the main aircraft engines and the APU (Auxiliary Power Unit) and GSE (Ground Support Equipment) are the most important sources of air pollutant emissions at airports. Considering

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Copenhagen, London-Heathrow, Brisbane and San Diego airports, Winther et al. (2015) estimate that the influence of NOx emissions produced by GSE, APU and main engines range between 5% and 9%, 2% and 9%, and 87% and 93% respectively, taking into account the airport as a whole, in the inventory that these authors develop for Copenhagen Airport (CPH) detailing the general contribution of main engines, APUs and GSEs in the movement area and at the apron level. If the apron subsystem is the only one under consideration, GSEs produce 63% of NOx emissions, 75% of Particulate Matter (PM) and 24% of fuel consumption. This shows that the apron operational mode (aircraft-GSEs) and the policy for stand allocation and use, when considered jointly, can present optimization points regarding the operational and environmental dimensions. This issue is the focus of this study, which analyzes the contribution of aircraft, GSEs and overall emissions under different management models of parking stands. Stettler et al. (2011) analyze the impact of the different sources in UK airports and reach the conclusion that aircraft are the main source regarding PM, emitting 47% of it, whereas GSEs emit over 66% of the gases related to OC (organic carbons) and are also responsible for 28% of the total particulate matter emitted. Other studies highlight the importance of GSE emissions in airport surroundings, which have reached 5% compared to all sources (including the LTO cycle) regarding NOx, despite not taking into account the contribution from the circulation of said vehicles on the apron (Fleuti, 2014).

In this context, this research develops a model allowing us to measure the emissions produced during service (loading and unloading stages) and the GSEs circulation on apron in order to provide real values of pollution produced by support vehicles. In order to do that, through the model, the user has the chance to characterize the apron and include arrival and departure specifications for each aircraft according to each stand. Using this information, the model processes the data and obtains the emission levels produced by GSEs and pollutant gases, along with all the distances covered and the number of vehicles required to provide the requested service. This tool will be applied to an airport (case study) in order to observe and compare the values given by the model.

1. Literature review

Over the last two decades, Academia has provided a significant amount of research regarding the impact, calculus, estimations and other studies (e.g., carbon footprints) on emissions produced by aviation, both globally (as an industry) and locally, limited to airports and/or influence areas near them. Regarding the latter, which includes the subject matter of this work, it can be stated that, although the topic is quite similar in most works, the main difference lies in where the analysis is carried out (the country, region, city, airport included in the case study). Additionally, there are differences in the approaches, such as: (a) calculation and estimation of airport air quality resulting from aircraft emissions in certain land operations (Ashok et al., 2017; Martini et al., 2013); (b) calculation of aircraft emissions in operations below 3000 feet, including take-off and landing cycles – LTO – (Tokuslu, 2020; Bo et al., 2019; Yang et al., 2018; Vujovic & Tedorovic, 2017; Xu et al., 2020); (c) influence of flight frequency on air pollution in the airport area, particularly the emission of particulate matter (Dong et al., 2020); (d) general analysis per country of environmental effects (e.g., air quality) produced by aviation in the national airport network (Grampella et al., 2017; Hepting et al., 2020); (e) study of the impact on the air quality around the airport (outer) area due to the emissions of different sources both inside and outside of the airport (e.g. ground access) (Peace et al., 2006); (f) analysis of the impact of emissions, especially that of particulate matter (produced by aircraft in airports), on population health (Penn et al., 2017); (g) identification and calculation of the carbon footprint resulting from airport emissions (Postorino & Mantechini, 2014); (h) calculation of emissions and air pollution as a result of aircraft take-off and landing cycles (LTO) in the airport (Yilmaz, 2017; Song & Shon, 2012); (i) calculation of emissions and air pollution as a result of aircraft take-off and landing cycles (LTO) in the airport and also as part of the ground support teams, parking stations and (service) ground vehicles at the air level of the airport (Mokalled et al., 2018); (j) calculation of emissions of aircraft APUs when they are on the ground (at the airport) (Padhra, 2018); and finally (k) development of an inventory of aircraft emissions during take-off and landing cycles (LTO), of the aircraft APUs, and of the service, assistance or ground vehicles (Winther et al., 2015; Stettler et al., 2011).

2. Conceptual framework

Both airport capacity and sustainability include the idea of environmental limits (Upham et al., 2003). An airport's environmental capacity is mainly a function of its infrastructure, operation and management, and of how many of the associated impacts the social and natural environments of the airport are willing to tolerate. Some authors (Kazda & Caves, 2000) state that there are several key factors that play an important role in the improvement of airport capacity. They include: Arrival/departure/surface management integration; optimization management; surface surveillance improvement and Airport collaborative decision-making.

Aircraft support vehicles on apron influence these four aspects. Movement management and optimization, as well as operation, challenge all parts involved (manufacturers, airlines, airport administrators, among others) to provide operative compatibility with existing infrastructure procedures and requirements.

For instance, in some airports with A380 operation, due to a greater demand of electrical energy in subsystems, systems of fixed terrestrial energy had to be modified and vehicles with a bigger wastewater capacity and operative altitude were developed. Additionally, more powerful tow trucks were required (Hamel et al., 2007). That is to say, the acquisition of new technologies, like aircraft, influences the operation and acquisition of associated support vehicles. In turn, with the aim of attaining sustainability and a lower associated environmental impact, towards the year 2030, all aircraft support vehicles should be emission free at taxiing (Darecki et al., 2011).

The agreed methodology to reach said goal is the use of electric vehicles. Generally, impacts of network energy consumption on air quality are considerably lower than those of local combustion emissions while obtaining an equivalent amount of energy. A globally used indicator is that of premature deaths. Yim et al. (2012) estimated that electrifying land support equipment in the airports of the United Kingdom in 2005 would reduce the number of premature deaths attributable to airport emission on those airports by 28%.

Through an analysis of operational and environmental advantages, as well as different technologies applied to GSEs, Azorín Gonzalez et al. (2013) conclude that optimization of future aircraft land operations cannot be understood without a comprehensive study of the apron. The importance of management and optimization has led to real-time monitoring of the movement of vehicles on the apron with the aim of characterizing them and minimizing aircraft emissions and associated fuel consumption. Such is the case of Alomar et al. (2017), who developed a base model showing that management efficiency of apron support vehicles largely depends on monitoring parameters and their level of detail. Additionally, they foresee that correct GSE management not only increases productivity, but also decreases carbon emissions.

Losses due to poor GSE management are not the result of environmental consequences alone. Jaehn and Neumann (2015) provide a specific comprehensive vision of the aircraft boarding problem and existing boarding strategies, where they prove that economic losses associated with each minute of delay are, on many occasions, explained by the different aircraft support vehicles.

In this same context, poor GSE management produces enormous negative results in the system, due to the fact that they affect not only the airline, but also every company with which the supplier deals. Taking into account boarding times and their consequences, Malandri et al. (2019) have researched the effects produced by management of land operators in airports and proved that efficiency, punctuality and regularity of aircraft operations are highly compromised by the management of land operators.

Future aircraft concepts aim at fulfilling ambitious objectives of emission reduction in the existing land management procedures and the associated infrastructure requirements (Schmidt et al., 2016). Having established a methodology to estimate turnaround time, Schmidt et al. (2016) show how influential position, loading and unloading are, among others, when the aim is characterizing the variables to be taken into account by new GSE development to accomplish a more efficient operation.

A ground processor gathers all the information by means of which real-time planning can recognize different actors and vehicles to be used, and act automatically. Evertse and Visser (2017) show that by updating the operational and taxiing status of vehicles every 20 seconds, it is possible to obtain a better response when there are unexpected disturbances in traffic flow. This type of technology of transport movement control measurement is used in different industries. Yang (2014) has analyzed problems regarding vehicle movement on a container terminal based on simulations.

It is clear that the GSE operation influences several aspects of aircraft operation. Proper aircraft operation and management result in an increase in capacity and a significant reduction of associated emissions. Taking into account gaseous emissions produced by both aircraft and GSEs, and the influence of the management model for the average delay per aircraft, Sznajderman et al. (2021) analyze the concept of a hybrid apron with a fixed number of parking positions.

This paper tackles the development of a methodology taking into account emissions produced by GSE service and traffic, and deepens the analysis by studying previous models related to emissions produced by these vehicles in service. Additionally, it develops a method to provide sustainable and efficient use of those vehicles.

The first model is the sophisticated approach proposed by ICAO (2007). This manual proposes a method to quantify GSE emissions produced during aircraft service. Below is Equation (1) for quantifying emissions according to GSEs and gas for the sophisticated model:

$$E_{k,i} = P \cdot fe_i \cdot f_d \cdot fc_j \cdot t_j\,, \tag{1}$$

where: $E_{k,i}$ – total gaseous emission according to the gas "i" produced by analyzed GSE "k", g; P – GSE equipment brake power, kW; fe_i – Emission factor of contaminant in service, in relation to the GSE equipment, $\frac{\text{g}}{\text{kW h}}$; f_c –loading factor of the GSE equipment; f_d – deterioration factor of the GSE equipment; t_j – ICAO measure the service time of each GSE according to each airport planning, h.

Another important model is that of Fleuti (2014), where the author proposes a similar model to the one explained before to quantify emissions in Zurich Airport. Just like the ICAO model, this one takes into account the engine power, loading factor, emission factor and time. However, it differs from the previous method in that this one characterizes aircraft by their size and whether they use the ramp or not, distinguishes between arrivals and departures, and introduces the emission reduction margin, m, by identifying non-exhausted limits per gas (Equation (2)).

$$E_{k,i} = P \cdot f_{ei} \cdot m \cdot fc_j \cdot t_j, \tag{2}$$

where: $E_{k,i}$ – total gaseous emission according to the gas "*i*" produced by analyzed GSE "*k*", g; P – GSE equipment brake power, kW; f_{ei} – emission factor of contaminant in service, in relation to the GSE equipment, $\frac{\text{g}}{\text{kWh}}$; f_c – loading factor of the GSE equipment; m – emission limit margin that, according to the Federal Office for Environment, are not exhausted; t_j – ICAO measure the service time of each GSE according to each airport planning, h.

From the analysis of these methods, it is deduced that these calculated values do not take into account emissions produced during GSE circulation between aircraft, and between their base stations and aircraft. Besides, times (t_j) along with loading factors are constant features. Therefore, the proposal of this methodology arises, the aim of which is to deepen the calculation of emissions produced by GSE vehicles throughout the operation. In order to do that, the user needs to know certain specific pieces of information regarding not only GSEs, but also the airport and operating aircraft infrastructures, among others.

3. Model development

As has been described, models or methodologies developed to quantify emissions of GSE vehicles take into account the service time but not the circulation or the loading and unloading stages. Sznajderman et al. (2021) developed a preliminary model considering the assignment of loading factors according to the discretization of service and circulation operating times. Emanating from that, the analysis of the assignment of each base according to the GSE group has been deepened, resulting in a more complex and advanced model presented up below.

Next, Equation (3) for the model to measure emissions produced by service and traffic is put forward. It is important to highlight that power, and emission and deterioration factors are an essential part of the characteristics of both GSEs and gases to be analyzed, which, along with the number of required vehicles (A_k), are common to both service and traffic. The first term of the square bracket on the equation corresponds to the four states for unloading and loading during the GSE service to the aircraft. The second term depends on traffic, taking into account the round trip, where a loading factor is assigned according to the distance to be travelled.

$$E_{k,i} = P_k \cdot fe_{i,k} \cdot fd_k \cdot \sum_{k=1}^{n} A_k \left[\sum_{j=1}^{8} \left(fc_j \cdot t_j \right) + \sum_{k=1}^{2} fc_k \frac{d_k}{v_k} \right], \quad (3)$$

where: $E_{k,i}$ – total gaseous emission according to the gas "i" produced by analyzed GSE "k", g; P – GSE equipment brake power, kW; fe_i (s) – emission factor of contaminant in service, in relation to the GSE equipment, $\frac{\text{g}}{\text{kW} \cdot \text{h}}$; $f_{ei,k}$ (c) – emission factor of contaminant in traffic, in relation to the GSE equipment, $\frac{\text{g}}{\text{kW h}}$; f_{c_j} – GSE equipment loading factor per discretized time j, according to the loading and unloading operation; f_{ck} – loading factor for the round trip; f_{dk} – deterioration factor of the GSE equipment; V_k – GSE equipment speed, $\frac{\text{km}}{\text{h}}$;$d_k$ – travel distance km; t_j – GSE discretized times for loading and unloading, h; A_k – amount of GSEs required per aircraft for each operation.

On the basis of the foregoing, the process of quantifying gaseous emissions produced by GSE service are the result of adding the emissions produced during service and traffic. The service provided by GSEs starts after aircraft arrival, when several different teams begin to perform their duties both in parallel and consecutively. During this process, vehicles have the task of unloading and loading all that is necessary for the next flight. In order to ground these calculations in reality, a discretization of times at different stages (wait, connection, service and disconnection for unloading and loading functions) is proposed and shown in Figure 1a. Hence, a more accurate model is put forward by assigning a loading factor to each stage for every GSE. Emissions produced during service essentially depend on discretized times and loading factors, according to the proposed stages, and also on the particular technical characteristics of GSEs.

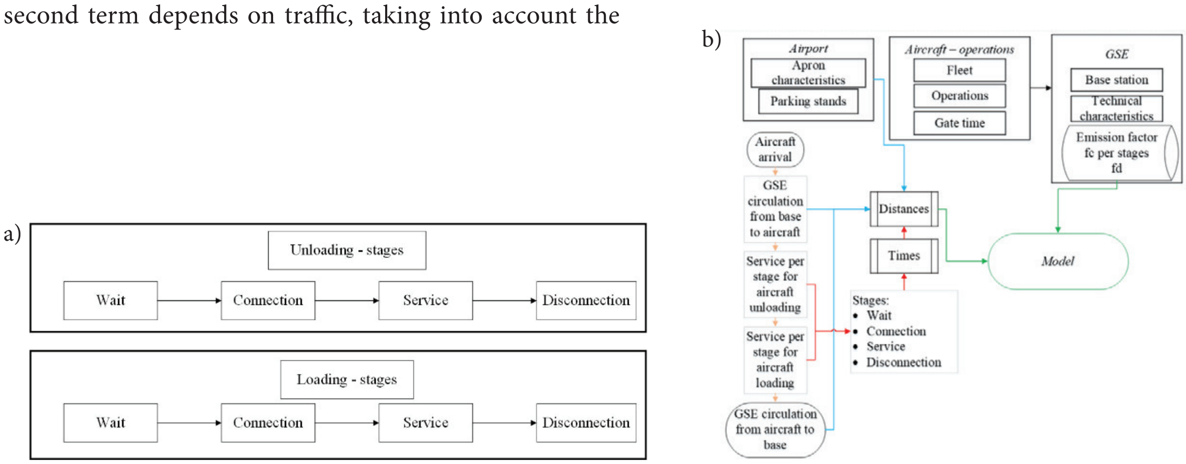


Figure 1. Process and data to be entered into the model: a – service processes. Discretization of service time at stages for general GSE loading and unloading; b – logical work process to determine air pollution and number of required vehicles (source: authors)

Traffic refers to the movements that GSEs can make between each base station and the aircraft parking stands of each group. Considering these emissions, along with those of service, the model takes into account the whole process involving GSEs on apron. These distances can be calculated by visualizing movements using GPS, parameterizing the apron, etc.

As shown in Figure 1b, the model to measure emissions is fed with travelled distances due to traffic and service times according to the different stages. The former depends mainly on the specific physical characteristics the apron, whereas the latter derives from the service stages of each GSE, which is not specific to any airport. The model adds ups emissions produced by traffic and service, and the gas according to the emission factor. This discretization allows us to link GSEs with the services for the demands under consideration. This makes it possible to nullify the A_k factor (amount of GSEs) if the aircraft does not need that.

4. Ground support equipment

4.1. GSE factors associated with the model

Loading factors (f_c) are those affecting maximum power. Northeast States for Coordinated Air Use Management & Center for Clean Air Policy (2003) define loading factor as the relation between output power and nominal power. According to Carl Moyer Program (1998), the loading factor is an indication of the amount of work carried out, on average, by an engine with a particular application, stated as a nominal power fraction. On traffic, these factors vary according to the engine demands for average speed on the assigned ramp. In the case of service, values can be taken according to loading and unloading operations of baggage, goods, passenger movement, etc. All values found in the bibliography are averages per vehicle for the service supplied to the aircraft. The sources identifying different vehicles and assigning fc are listed in Table 1.

Emission factors (f_e) are calculated by putting engines on test rigs on maximum power and they are classified according to the type of fuel. On Table 2, there appear emission factors according to different bibliographies. There are several previous works on Table 2 identified as "emission factors", indicating a broad range of air pollutants present in gaseous emissions related to aviation, which could have consequences on human health and the environment. This analysis takes into consideration the basic ones among them, i.e., CO, NOx, SOx, HC, PM_{10} and CO_2. Even though the latter is not a part of said group, it is usually included in inventories as it is a worldwide concern.

The deterioration factor (f_d) amplifies the value of emissions according to the years of use. For each contaminant, there are two types of auxiliary coefficients to make the calculation according to the corresponding power range (A and b). Furthermore, it is necessary to know the model of the analyzed vehicle and its lifetime. In order to do that, the use of equation 4 alluded to by the EPA (U.S. Environmental Protection Agency – Office of Transportation and Air Quality, 2005) is proposed:

$$f_d = 1 + A\left(\frac{GSE_{year}}{GSE_{usefull\ life}}\right)^b. \tag{4}$$

The time required to supply aircraft with services directly influences the use of airport gates and depends on the type of aircraft, the number of passengers and the loading and unloading of baggage, among other things. Software programs currently employed, such as Emissions

Table 1. Loading factors for GSEs according to the bibliography (source: authors)

Id	Source	Type	Characteristic
1	EDMS/AEDT 2d	Software	Database, vehicle-dependent FC, model, and fuel
2	Zurich Airport – Aircraft Handling Emissions	Zurich methodology magazine	FC per vehicle
3	EPA	Report	2 FC: EPA and NESCAUM – table II-16
4	Draft airport ground support equipment	Section	Default FC – table 6
5	Expansion of Hong Kong International Airport	Appendix – EDMS – USEPA NONROAD	EDMS database and surveys – Chapter 5 Hong Kong Expansion
6	GPU exhaust emissions	EF according to Euromot 1, EUNRMM, ZRH/FOCA	GPU value only in Zurich
7	ICAO – Doc 9889	Guidance – Manual	Default FC – page 71. Factor range

Note: where the reference of each Id is:
1: AEDT 2d (U.S. Department of Transportation, 2019);
2: Fleuti (2014);
3: NESCAUM and CCAP (Northeast States for Coordinated Air Use Management & Center for Clean Aair Policy, 2003);
4: Carl Moyer Program (1998);
5: Airport Authority Hong Kong (2014);
6: Fleuti (2006);
7: International Civil Aviation Organization (ICAO) (2007).

and Dispersion Modeling System (EDMS) or Aviation Environmental Design Tool (AEDT) (Table 3), use the times recommended by airport planning for each aircraft. However, Vicente (2010) and Sanchez (2009) discretize vehicle service times. As mentioned before, the model considers four stages for both aircraft loading and unloading. In addition, Table A1 shows the time in hours according to aircraft per GSE.

The number of vehicles required per aircraft (A_k) will depend on the service (Full-Service Carrier o Low-Cost Carrier), the aircraft itself, the number of passengers and the infrastructure of each airport. Vehicles have specific characteristics depending on the type of operation of aircraft. Table 4 shows vehicle characteristics according to suggested bibliography.

Table 2. Emission factors (source: authors)

Id	Source	Characteristic	Analyzed gases	Unit
1	EDMS/AEDT 2d	Database, vehicle-dependent FC, model, and fuel	CO, HC, NO_X, SO_X, PM	g/HP.h
2	Zurich Airport – Aircraft Handling Emissions	Zurich methodology magazine	CO, HC, NO_X, PM	g/kWh
3	Expansion of Hong Kong International Airport	Appendix – EDMS- USEPA NONROAD	CO, HC, NO_X, SO_X, PM_{10}	g/hp.h
4	GPU exhaust emissions	EF according to Euromot 1, EUNRMM, ZRH/FOCA	CO, NO_X, PM, HC, CO_2	g/kg diesel
5	EPA	USEPA's NONROAD; manual	HC, CO, NO_X, SO_X, PM	g/hp.h
6	New Zealand Government	Emissions per consumption; per fuel;	CO_2	CO_2/l; CO_2/km
7	European Environment Agency	Emissions per engine running	CO, NO_X, VOC, CH_4, CO_2, N_20, NH_3, SO_X, PM	g/km
8	Federal Office for the Environment	FE calculated on HBEFA	CO, CO_2, HC, N_2O, NO_X, PM	g/km
9	IPCC	Road transport default CO_2 emission factors	CO_2	Kg/TJ (g/HP h)

Note: where the reference of each Id is:
4: US EPA (United States Environmental Protection Agency, 2010);
5: Ministry for the Environment – New Zealand Government (2019);
6: Ntziachristos and Samaras (2000);
7: Federal Office for the Environment FOEN (2010);
9. IPCC (Intergovernmental Panel on Climate Change, 2006).

Table 3. Times according to loading and unloading stages (source: authors, 2021)

Source	Characteristic	Unit
Analysis of Ground Handling Characteristics of Innovative Aircraft Configurations	Measurement and mathematical models of loading and unloading times per stages	s
Ground Handling Simulation with CAST	Comparison with LCC. Gantt Diagrams per GSE/stage	m
Airport Air Quality Guidance Doc. 9889	Default value range	m
EDMS	Default values	m
Expansion of Hong Kong International	Values provided by the airport according to arrival and departure, operation and movement.	m

Table 4. Technical specifications and power plant according to the suggested bibliography (source: authors)

Source	Characteristic	Unit
EDMS	Default values per GSE and fuel	BHP
Airport Air Quality Guidance Doc. 9889	Value range per GSE	kW
Expansion of Hong Kong International	Diesel. Average value	HP
Aircraft Handling Emissions	GSE list in Zurich. Power range per GSE	kW
Draft airport ground support equipment	GSE power range in California – Table 6	HP
GPU exhaust emissions	All GPU power in Zurich – Table 2-1	kW

4.2. Operational characteristics of GSEs

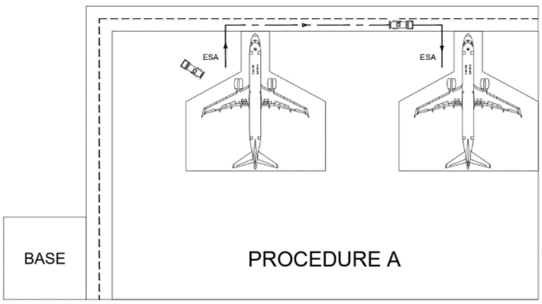
Variables presented in the equation of the model, considering emissions both during service and traffic, also depend on a series of operational characteristics. Some of them are detailed hereafter:

The number and arrangement of GSEs depend on the service required by the airline during the flight. For Full-Service Carrier (FSC) flights, all service vehicles are used; whereas, for Low-Cost Carrier (LCC) flights, some are exempted from assisting the aircraft due to company policies and airport characteristics. Gomez et al. (2009) analyze the characteristics and new procedures developed by LCC regarding land assisting operations.

Aircraft load capacity and number of passengers on board directly influence some of the required GSEs, for instance, the number of buses required to transport passengers if the stand does not have a boarding bridge.

Services provided to the aircraft are limited to loading and unloading of cargo and passengers. Therefore, arrival and departure times of the aircraft are essential for the model to be able to identify the service and traffic taking place in those two processes. Types of procedures: For practical purposes, this paper takes into account the classification of each GSE in different types of procedures (A and B) according to specific functions. Type A procedure: according to the availability of the equipment, a trip between temporal parking stands (ESA) is simulated, depending on the number of aircraft stands. Type B procedure: vehicles must always return to a specific operation area after providing the service to the aircraft. Therefore, transfer distance is the traffic towards each aircraft parking stand and the return to its determined fixed area before moving to another aircraft (base). Table 5 and Figure 2 summarize and group what has been previously stated.

a)



b)

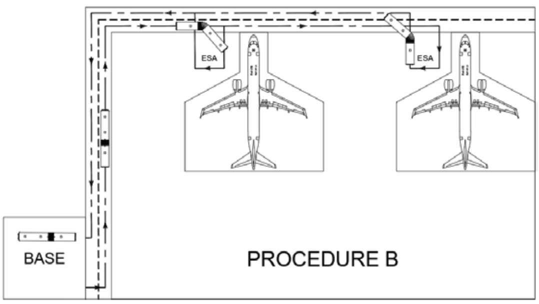


Figure 2. Procedures: a – illustration of procedure A between two parking stands; b – procedure B in which vehicles leave the base to assist an aircraft (source: authors)

Table 5. Types of procedure according to parking stands of GSE vehicles (source: authors)

Types of procedures	GSE	Parking stand
A	Belt load, Tug, GPU, Passenger stair, Cleaning, Water supply	Located at the equipment staging area (ESA) according to service time per aircraft[1].
B	Baggage tractor, Bus, Catering truck, Fuel	Fixed parking area[2]. Catering vehicles are parked outside of the apron. The tanker has assigned base stands in the fuel plant on the airport grounds

Notes: [1]The traffic sequence on the apron depends on the availability of each service group of vehicles; [2]It is chosen in such a way that the best option is that the equipment is always moving between this point and each aircraft parking stand.

5. Model application

The airport location adopted as study case for the model developed and presented here is the Gustavo Rojas Pinilla International Airport (SKSP) located on San Andrés Island (insular region of Colombia in the Caribbean Sea). This place is 1.3 km northeast of the center of San Andrés Island.

5.1. Hypothesis

This study is made in the context of commercial air transport service (scheduled and non-scheduled) for international and cabotage or regional operations. Aiming at being conservative and due to the available information, all flights considered are point-to-point with full service and no scales. This study excludes air conditioning units, air starter units, freight elevator vehicles, vehicles for passengers with reduced mobility and de-icing vehicles.

In this study, it is considered that all analyzed vehicles use diesel fuel due to the fact that they are usually pieces of equipment with great power. In fact, the action plan of the Argentine State carried out by ANAC and the Transport Ministry of Argentina (ANAC & Ministerio de transporte Argentina, 2021) states that 99% of GSEs use this type of fuel.

As for CO_2, the emission factors used are those provided by IPCC (id. 9). For the rest of the gases, AEDT (id. 1) is used. Table 6 shows the values adopted and used in the model for the study case.

To calculate the damage factor, it is necessary to consider the service time of vehicles and their lifetime. Based on the collected data, it is proposed that all vehicles have 7 years of service time with a lifetime of between 10 and 14 years, depending on the vehicle. Table 7 shows the values adopted and calculated according to Equation (4), respectively.

All service vehicles are considered to be located at the “Base”, except for fuel-supply trucks, which are located at the Planta Chevron Aviación.

Table 6. Emission factors per gas analyzed (source: U.S. Department of Transportation (2019) and US EPAs (United States Environmental Protection Agency (2010))

Ground Support Equipment	GSE	Emission factor gr/HP.h					
		CO_2	CO	HC	NOx	SOx	PM
GPU	GPU	198	0.96	0.30	4.13	0.05	0.25
Catering	CAT	198	0.45	0.20	1.04	0.04	0.07
Tug	TUG	198	1.50	0.33	4.49	0.05	0.29
Baggage	BAG	198	3.87	0.37	4.26	0.06	0.50
Belt Load	BEL	198	2.55	0.38	4.54	0.06	0.40
Water Truck	WAT	198	0.80	0.29	2.90	0.05	0.13
Lavatory truck	LAV	198	0.73	0.27	2.71	0.05	0.10
Fuel	FUE	198	0.61	0.25	2.18	0.05	0.06
Stair truck	STA	198	0.80	0.29	2.89	0.05	0.13
Bus	BUS	198	0.11	0.13	2.50	0.22	0.17
Cleaning	CLE	198	0.65	0.26	2.42	0.05	0.07

Table 7. Lifetime and deterioration factor according to analyzed GSEs and gases (source: authors)

GSE	Lifetime (years)	CO_2	CO	HC	NO_X	SOx	NOx
GPU	14	1	1.064	1.012	1.003	1	1
CAT	10	1	1.090	1.016	1.005	1	1
TUG	13	1	1.069	1.012	1.004	1	1
BAG	11	1	1.082	1.015	1.004	1	1
BEL	11	1	1.082	1.015	1.004	1	1
WAT	10	1	1.090	1.016	1.005	1	1
LAV	13	1	1.069	1.012	1.004	1	1
FUE	14	1	1.064	1.012	1.003	1	1
PAS	14	1	1.064	1.012	1.003	1	1
BUS	10	1	1.090	1.016	1.005	1	1
CLE	13	1	1.069	1.012	1.004	1	1

Table 8. Number of vehicles required per analyzed aircraft (source: authors)

GSE	A319	A320	A321	B737	E190
GPU	1	1	1	1	1
CAT	1	1	1	1	1
TUG	1	1	1	1	1
BAG	2	2	2	2	2
BEL	1	1	1	1	1
WAT	1	1	1	1	1
LAV	1	1	1	1	1
FUE	1	1	1	1	1
PAS	1	1	1	1	1
BUS	2	2	2	2	2
CLE	1	1	1	1	1

The number of GSE vehicles per aircraft depends on the requested service. This case study is analyzed considering a standard turnaround for commercial flights. Table 8 shows the amount of equipment requested per aircraft.

5.2. Reference airport characterization

As a first step, the reference airport is characterized. This characterization involves the identification and description of the main elements that make up the airside. The study of runways, taxiways and the apron are essential to understand the operations carried out in airports in detail.

Parking stand distribution allows for the provision of services to a certain number of aircraft. This capacity is reflected in the characterization of the airport ramp. This considers the following:

1. Number, type and geometrical description of the apron.
2. Number of parking stands and use restrictions per aircraft.

This analysis has great importance, since the circulation routes of ground support vehicles (GSE) will be larger or smaller depending on the placing of the aircraft parking stands and of the base stations for each of the identified vehicles. The grounds have a passenger apron with 5 parking stands, 3 of which have boarding bridges.

5.3. Analysis of the operational fleet

There are operation data for every month in the year 2019 (Aerocivil, 2021). Since one of the aims of this paper is quantifying the GSEs required according to demand, the study has to cover one day. Monthly movements for the year 2019 were the first ones analyzed. This showed that July was the month with the most passenger transportation operations, with 1483 monthly operations (Aerocivil, 2021).

The chosen day comes from dividing the operations of the month in question by the number of days in said month. This gives us the number of total operations per aircraft in the day as a result, summarized in Table 9.

Table 9. Daily operations per aircraft (source: Aerocivil, 2021)

Aircraft	A319	A320	A321	B737	E190
Amount per day	7	11	5	5	1

5.4. Characterization of ground support vehicles

The GSE models used as reference for calculations were taken from the U.S. Department of Transportation (2019) software database. These show the characteristics described on Table 10.

Granda et al. (2021) propose an analysis of the loading factors in circulation of each GSE according to the interacting forces of the vehicles and depending on variables like mass and front area, influencing certain maximum power percentages (Table 11).

5.5. GSE circulation

Firstly, GSE parking stands for Type A procedures were identified (see Table 5). These refer to the equipment staging areas (ESA) located around the aircraft parking stand. Secondly, GSE parking stands for Type B procedures were identified. According to the identification of procedures and aircraft parking stands, as well as each GSE equipment base station, the model quantifies the distances of each vehicle depending on the requested availability in service and circulation.

5.6. Delimitation of GSE optimal amount

The distances between parking stands are calculated using the developed model. In order to do this, it is necessary to upload an image of the apron and identify each parking stand and the angles (or nodes) indicating a change of direction in the circulation roads. The nodes should be positioned over the service roads in such a way as to allow the restriction of GSE movement on the apron. Then, the maximum number of operations that can be carried out by the same group of service vehicles is determined. The model compares the aircraft arrival dates and determines which ones can receive assistance according to the corresponding service and circulation times.

Once the service and circulation stages come to an end, the vehicle will be available for use once again. This way, the circulation cycles (to)-service-circulation(back) for each of the GSEs were established and the final result was the optimal number of vehicles necessary to meet the aircraft demand.

5.7. Operating times

The model proposes a division of times during service. This entails proposing 2 stages for aircraft service: unloading and loading. In both stages, discretization suggests four states, such as stated by Sznajderman et al. (2018): Wait, Connection, Service and Disconnection. The values shown in Appendix A have been measured and statistically worked on in order to standardize the values. Regarding the service columns, in order to work with fewer mistakes, the model identifies these particular times for each aircraft in its corresponding Airport Planning (AP). It is important to note that, where there are no values, it is considered that the GSE for a particular stage is not required. In the case of LAV and CLE GSEs, the values are issued during the service since a vehicle is not required, but circulation emissions are considered nonetheless.

5.8. Results

Based on the obtained results (see Table B1), the relationship between service emissions and circulation emissions seems to depend on the apron and the location of each GSE equipment base station. In the study case, because the airport is one with a low number of operations (which influences the apron characteristics), circulation emissions are significantly lower (it provides approximately 10% of the total average GSE emissions) when compared to service emissions. This could be affected if, for instance, the fuel base stations (FUE) were considered to be further from the place in which they were located. CO_2 emission values, resulting from the CO_2 emission factor, are high compared to other gases. If the other gases are analyzed, it is noted that NOx takes precedence over the others, since it is one of the main gases directly affecting health. Appendix B shows the amount (in kg) of the emissions produced

Table 10. Reference models for calculation (source: U.S. Department of Transportation, 2019)

GSE	GPU	CAT	TUG	BAG	BEL	WAT	LAV	FUE	PAS	BUS	CLE
Model	TLD 400Hz AC	Hi-way F650	Tug GT-35	Tug MA 50	Tug 660	Wollard TWS-402	Wollard TLS-770A	Titan Aviation	Wollard CMPS-228	Volvo Neobus B7R	Hi-way F650
Power [kW]	194	157	55	64	64	175	175	268	48	216	157

Table 11. Calculated loading factor per circulation for GSEs performing movements (source: authors)

GSE	CAT	LAV	WAT	BAG	BEL	BUS	PAS	TUG	FUE
LF	0.10	0.02	0.03	0.04	0.04	0.07	0.09	0.22	0.19

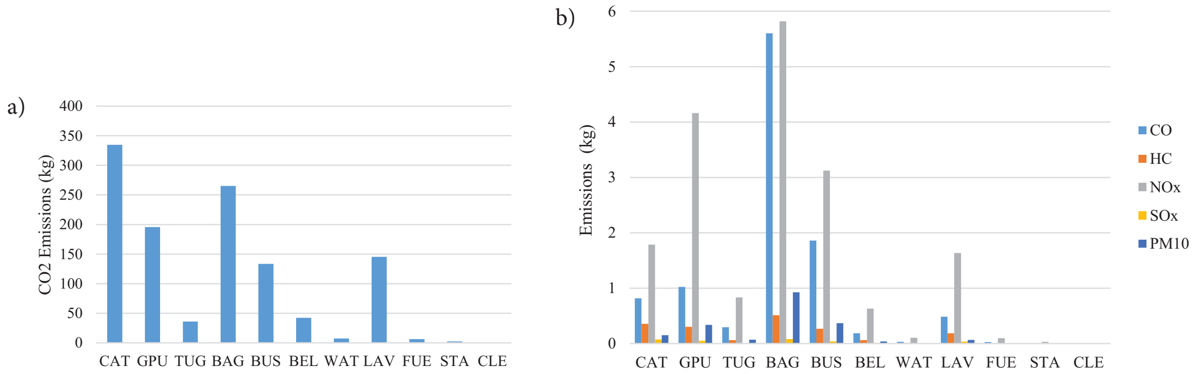


Figure 3. Emissions of each gas per GSE: a – CO_2 emissions per type of GSE; b – CO, HC, NOx, SOx and PM10 emissions per type of GSE (source: authors)

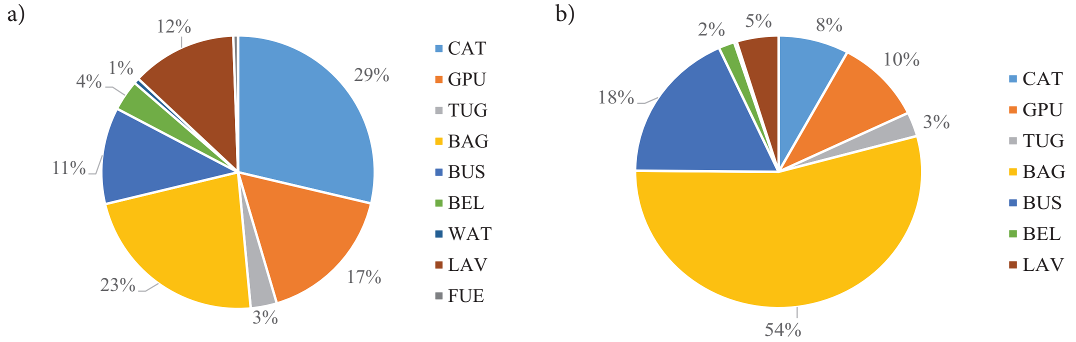


Figure 4. Emission distribution per GSE: a – CO_2 analysis; b – CO analysis

as a result of the use of each GSE for the service and circulation functions. The relationship between service and circulation is constant in all the analyzed gases.

Aiming at more easily visualizing the total emissions produced by each vehicle of each gas, Figure 3 shows where the emissions per equipment vary for CO_2 and for the rest of the gases respectively.

On a different note, it is interesting to analyze emissions of different gases per GSE. The results of such analysis allow us to identify the vehicles producing more pollution and, based on this, the possible initiatives for mitigation measures. Figure 4 shows GSE contribution for CO_2 and CO. It can be seen that, for CO_2, vehicles CAT, BAG and GPU add up to almost 70% of the emissions, whereas for CO, vehicles GPU, BAG y BUS provide over 80% of the total.

In addition to the results shown by the model, Appendix C provides an opportunity to view the emission values for the same conditions arising from the calculations made according to the ICAO methodology (Eq. (1)). It is important to state that, for this comparison, the inputs (the airport, operation number and GSEs characteristics) are equal to those used in the developed model. If the values of each gas per GSE or the total values are analyzed, it is possible to state that the ones resulting from the model are lower than those of ICAO. In fact, it can be calculated that the average of the total values per gas is 65%.

Conclusions

Developed model enables to characterize and measure the total amount of gaseous emissions during the operation of aircraft support vehicles. The model analyses not only not only to analyze the emissions produced during aircraft service, as most existing models do, but also takes into account the movement and traffic in the corresponding airport infrastructure. Regardless of apron geometry, the model carries this out by parameterizing all possible routes after the user enters the data for the apron, GSE aircraft parking stands and base stands. Furthermore, service emissions are more accurate since the times per stage are discretized for both loading and unloading operations. Adjusts the loading factor for each of the above-mentioned stages in their corresponding time and prevents from associating an average time with an average loading factor.

The advantage of this model is the high accuracy with which it represents real situations by offering certain flexibility in the type of service and equipment to be used by GSEs. Furthermore, this model can be applied to any kind of apron, where the distance travelled by each vehicle is measured according to the assigned procedure and the type of aircraft operation (FSC or LCC). Furthermore, even though the model needs a huge amount of data to be applied, this does not constitute a problem since there are usually data sources available at all airports (which, sometimes, are highly rich and detailed). Then, the hypothesis that complies with the requirements can be applied to use the model. Another advantage of this model is that it quantifies the emissions of each GSE, which allows for the identification of those GSE that contribute the most to the total amount of emissions produced both in service and during circulation. This, in turn, allows for the proposal of different strategies for mitigation measures, such as electrifying specific equipment, moving or adding GSEs base stations and reducing circulation, etc.

Using this model allows to adjust values and be less conservative compared to other existing methodologies. Currently, to inventory all the sources of the emissions produced in airports, the methodology provided by OACI is generally used. Even though this methodology takes into account a huge number of variables, it is still conservative. In fact, the emissions calculated by the model are (see Table C1), in average, 63% lower, even though it includes emissions produced by both service and circulation (the latter of which are not taken into account by the OACI methodology).

A future work to be carried out is the application of the model in several airports with different airport configurations. From then onwards, it is possible to ponder the relative importance of GSE pollutant input regarding different sources such as aircraft operation during the LTO cycle, the input of different specific sources and even the Ground Access Vehicles (GAV), among others.

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Appendix A

Table A1. Time in hours according to aircraft per GSE (source: authors)

GSE	Unload				Load			
	Wait	Connection	Service	Disconnection	Wait	Connection	Service	Disconnection
GPU	–	–	–	–	0.00	0.01	AP	0.01
CAT	–	–	–	–	0.01	0.03	AP	0.03
TUG	–	–	–	–	0.01	0.03	AP	0.01
BAG	0.02	0.01	AP	0.00	0.02	0.01	AP	0.00
BEL	0.03	0.01	AP	0.03	0.03	0.01	AP	0.03
WAT	0.01	0.00	AP	0.00	0.01	0.00	AP	0.00
LAV	–	–	–	–	–	–	–	–
FUE	–	–	–	–	0.24	0.02	AP	0.03
PAS	0.00	0.02	AP	0.00	0.00	0.02	AP	0.00
BUS	0.00	0.02	AP	0.00	0.00	0.02	AP	0.00
CLE	–	–	–	–	–	–	–	–

Appendix B

Table B1. Emissions according to service and circulation of all the analyzed gases per GSE group (source: authors)

GSE group		CO_2 (kg)	CO (kg)	HC (kg)	NOx (kg)	SOx (kg)	PM_{10} (kg)
CAT	Service	321.47	0.79	0.34	1.72	0.07	0.15
	Circulation	2.65	0.01	0.00	0.01	0.00	0.00
	Total	324.12	0.79	0.35	1.73	0.07	0.15
GPU	Service	194.85	1.02	0.30	4.15	0.05	0.33
	Circulation	0.68	0.00	0.00	0.01	0.00	0.00
	Total	195.52	1.03	0.30	4.16	0.05	0.34
TUG	Service	31.80	0.26	0.05	0.73	0.01	0.06
	Circulation	1.90	0.02	0.00	0.04	0.00	0.00
	Total	33.70	0.28	0.06	0.78	0.01	0.07
BAG	Service	251.17	5.31	0.49	5.51	0.08	0.88
	Circulation	1.13	0.02	0.00	0.02	0.00	0.00
	Total	252.30	5.33	0.49	5.53	0.08	0.88
BUS	Service	77.53	0.05	0.05	1.00	0.09	0.09
	Circulation	0.71	0.00	0.00	0.01	0.00	0.00
	Total	78.24	0.05	0.05	1.01	0.09	0.09

End of Table B1

GSE group		CO_2 (kg)	CO (kg)	HC (kg)	NOx (kg)	SOx (kg)	PM_{10} (kg)
BEL	Service	128.53	1.79	0.26	3.01	0.04	0.35
	Circulation	0.40	0.01	0.00	0.01	0.00	0.00
	Total	128.94	1.80	0.26	3.02	0.04	0.36
WAT	Service	34.93	0.15	0.05	0.52	0.01	0.03
	Circulation	0.45	0.00	0.00	0.01	0.00	0.00
	Total	35.39	0.16	0.05	0.53	0.01	0.03
LAV	Service	0.00	0.00	0.00	0.00	0.00	0.00
	Circulation	0.30	0.00	0.00	0.00	0.00	0.00
	Total	0.30	0.00	0.00	0.00	0.00	0.00
FUE	Service	132.58	0.44	0.17	1.49	0.03	0.06
	Circulation	4.88	0.02	0.01	0.05	0.00	0.00
	Total	137.46	0.46	0.18	1.55	0.03	0.06
STA	Service	4.52	0.02	0.01	0.07	0.00	0.00
	Circulation	0.36	0.00	0.00	0.01	0.00	0.00
	Total	4.89	0.02	0.01	0.07	0.00	0.00
CLE	Service	0.00	0.00	0.00	0.00	0.00	0.00
	Circulation	2.41	0.01	0.00	0.03	0.00	0.00
	Total	2.41	0.01	0.00	0.03	0.00	0.00

Appendix C

With the aim of comparing the emissions quantified by the model and those put forward by the ICAO sophisticated model (presented on Equation 1), the final values per gas according to each GSE for both methodologies are presented next.

Table C1. Comparison between ICAO methodology and the model (source: authors)

GSE	Emission ICAO (kg)						Emission Model (kg)					
	CO_2	CO	HC	NOx	SOx	PM	CO_2	CO	HC	NOx	SOx	PM_{10}
GPU	705	36	1	15	0	1	196	1	0	4	0	0
CAT	266	1	0	2	0	0	335	1	0	2	0	0
TUG	10	0	0	0	0	1	36	0	0	1	0	0
BAG	108	2	0	3	0	0	265	6	1	6	0	1
BEL	98	1	0	3	0	0	42	0	0	1	0	0
WAT	24	0	0	0	0	0	8	0	0	0	0	0
LAV	38	0	0	2	0	0	145	0	0	2	0	0
FUE	149	0	0	3	0	0	7	0	0	0	0	0
STA	27	0	0	0	0	0	2	0	0	0	0	0
BUS	103	1	0	2	0	0	134	2	0	3	0	0
CLE	48	0	0	2	0	0	0	0	0	0	0	0
Total	1.578	42	2	31	0	3	1.170	10	2	18	0	2