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EVALUATION OF SCENARIOS OF AIR POLLUTANTS EMISSIONS BY THE AIRPORT EXPANSION AND ASSOCIATED INFRASTRUCTURE - CASE STUDY OF THE EXTENSION OF VIRACOPOS AIRPORT AT CAMPINAS, SÃO PAULO, BRAZIL

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Abstract: The development of the airport segment faces environmental externalities especially related to the increase in emissions of Greenhouse Gases (GHGs) from combustion of fossil fuels by the aircraft engine, by the machinery for the maintenance of the planes and also by the vehicles used for passengers connections (private cars, taxicabs or public transportation system). In this scope, the current work presents the case study of the expansion of the Viracopos International Airport at Campinas – São Paulo, Brazil. To evaluate that, the methodology of the Intergovernmental Panel on Climate Change (IPCC) was implemented to estimate the emissions of GHGs by aircraft for the years 2008 (before expansion), 2012 (current picture) and 2018 (future scenario) observing the changes in demand for passengers and cargo transportation. To evaluate the emissions from the vehicles it was used the AIMSUN microsimulation software to estimate emissions in the years 2012 and to simulate sensitivity scenarios for the year 2018. It was found that the inventory of CO_2 emissions for both types of transports considered for the Viracopos airport showed similar orders of magnitude, what can be inferred about the equivalent contribution of these two modes on emissions of GHGs for the study area. These results may serve as a basis for establishing emission management plans of air pollutants by the competent organizations and to propose more targeted and effective measures to reduce the GHG emissions by these sources.

Keywords: Viracopos International Airport; air pollutants emission; GHGs; aircraft emissions; vehicle emissions; AIMSUN

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INTRODUCTION

Within the transportation segment, there is a strong emphasis on air pollution arising from the vehicular emission due to the growth in the fleet of light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) in recent years. LDVs tend to produce more carbon dioxide (CO_2) and hydrocarbons, and HDVs, more particulate matter (PM), nitrogen oxides (NO_x) and sulfur dioxide (SO_2) (Phuleria *et al.*, 2006; Barth *et al.*, 2004). Though, in Brazil the LDVs and HDVs are regulated by the National Environmental Council (CONAMA) with rigorous emission control programs, which have improved the development of new technologies and the enhancement of energy efficiency which decreased atmospheric pollutants emissions.

The contribution of air transportation on atmospheric emissions in the Brazilian scenario is barely studied. It is extensively known that aircrafts are more inefficient and larger than automobiles. Therefore, airplanes require greater amount of fossil fuel and consequently generate more combustion products (FLYING CLEAN, 2013).

An aircraft wholly supplied with jet fuel uses the same amount of energy that 3500 cars, which is equivalent to a passenger using six automobiles. On average, long-range aircrafts emit twice as much as cars per kilometer traveled per passenger while short-range aircrafts emit three times more (FLYING CLEAN, 2013).

The aircraft emissions are divided into about 70% of CO_2, almost 30% of water vapor and approximately 1% of other pollutants, which include carbon monoxide (CO), NO_x, volatile organic compounds (VOCs) and PM. These emissions can occur either close to the ground level as well as at high altitudes during the cruise phase of the flight. The ground level procedures make the engine spend a greater interval on the idle mode or near it, which is less efficient and allow the emissions of higher amounts of gaseous pollutants such as CO and VOCs (as happens, for example, during the taxiway). Most of the emissions occur at higher altitudes (ca. 90%); when the engine is in a high power operation, it emits more NO_x (such as during the takeoff and the cruise stages) (Hileman *et al.*, 2013; FAA, 2005).

In 2012 the vehicle fleet of the Metropolitan Region of Campinas (MRC) was approximately 1 million vehicles, considering LDVs and HDVs (CETESB, 2013). The compounds emitted by the combustion of fossil fuel in the engine are CO, NO_x, non-methane hydrocarbons (NMHC), aldehydes (RCHO), SO_2, CO_2 and PM. Evaporative emissions of unburned hydrocarbons are also a great contribution to atmospheric pollution, especially in low temperature combustion condition. The LDVs are the largest emitters of NMHC and CO, while the HDVs produce considerable amounts of NO_x and PM; motorcycles are the second largest source of emissions of CO and NMHC. All these categories contribute to the emissions of SO_2 since its formation is related to the consumption of fossil fuels with the presence of sulfur in the composition.

Therefore, the present work will address on the expansion of the Viracopos International Airport, located in the city of Campinas in São Paulo – Brazil, following the growth in the passenger´s demand in recent years (ANAC, 2013) and the resulting changes in GHGs emissions from the aircraft and the road network of the neighboring environment. This infrastructure can be perceived as a center of economic development. Furthermore, the results can serve as a guide to emission reduction public policy aimed at reduction of taxes and marketing strategies (Scheelhaase & Grimme, 2007; Barth el at., 2004).

CALCULATION OF AIR POLLUTANTS EMISSIONS

Aircraft emissions of atmospheric pollutants

The International Civil Aviation Organization – ICAO, in its Air Quality Manual for Airports, presents general approaches to quantify emissions from aircraft engines, with different levels of complexity, parameters and factors depending on the openness of the data and information (ICAO, 2011). The IPCC methodology reports three methods of quantification: Tier 1, Tier 2a and Tier 2b, differentiated according to the detailing level.

The Tier 1 method is used when there is no open data on the type of aircraft and the LTO stage accumulated (Landings and Takeoffs cycle). This method is based on the amount of fuel consumed by the aircraft multiplied by an average emission factor derived from the phases of the flight, considering that 10% of the amount of fuel is used at the LTO stage. **Equation (1)** considers the total emission (ET, in kg of pollutant) with the consumed fuel (C, in tons) and the emission factor (EF, in kg of pollutant per ton of fuel consumed).

$$E_T = C \times EF \qquad (1)$$

The Tier 2a and Tier 2b methods estimate emissions in LTO and cruise stages, whereas Tier 2b also takes into account the type of the aircraft. **Equation (2)** shows how to calculate emissions in LTO stages (E_{LTO}, in kg of pollutant), considering the emission factor in LTO (EF_{LTO}, in in kg of pollutant per LTO).

$$E_{LTO} = \left(\frac{number\ of\ landings\ and\ taskeoffs}{2}\right) \times EF_{LTO} \qquad (2)$$

The atmospheric emissions during the cruise stage (Ec, in kg of pollutant) are calculated considering the total fuel consumption (TFC, in tons); number of landing / takeoffs (LTO); fuel consumption per LTO (C_{LTO}, in tons) and the 10^3 conversion factor for kg to tons transformation, **Eq. (3)**.

$$E_C = \left(TFC - \frac{(LTO \times C_{LTO})}{10^3}\right) \times EF_C \tag{3}$$

Thus, the Tier 2a can be calculated by adding the emissions from LTO and cruise stage, as shown in **Eq. (4)**:

$$E = E_{LTO} + E_C \tag{4}$$

When calculating the Tier 2b method, there is the addition of the aircraft index (j), which is characteristic of the aircraft type, as shown in **Eqs (5)** and **(6)**. The sum of these emissions is also made by **Eq. (4)**.

$$E_{LTO} = \sum_j \left(\frac{number\ of\ landings\ and\ taskeoffs}{2}\right)_j \times EF_{LTO_j} \tag{5}$$

$$E_C = \left(TFC - \frac{\left(\sum_j LTO_j \times C_{LTO_j}\right)}{10^3}\right) \times EF_C \tag{6}$$

From an engineering view, the emission calculations are performed using the separation between the takeoff and landing operations (LTO) and the cruise stage due to different mechanical demands on the engine during these operations resulting in quite differences in pollutants emissions (Scheelhaase & Grimme, 2007).

Vehicles emissions of atmospheric pollutants

The vehicular emission calculation methods are constantly evolving, and are usually made by area or by segment methodologies. The area-method is based on information about energy consumption or fuel consumed per unit of area. Nevertheless, the segment-method uses a detailed analysis of the traveler behavior and the characteristics of the transport systems along the transport network (Pohlmann & Friedricj, 2013).

These emission calculation methods can be subdivided into categories according to the degree of detailing about the traffic behavior. Simulation models are widely used for the analysis of traffic behavior in transportation engineering. The microsimulation allows detailed studies of various technological scenarios in minor components of the transport network, with short-term responses of views and disregarding the choice of the transport modal.

In a study by Duarte & Paiva (2013), it was made an adaptation of the area-method through the relationship between the distance covered by each type of vehicle and the corresponding emission factor for each type of fleet in a corresponding year, considering the Brazilian scenario and the typical characteristics of the current fleet. In this work it was possible to estimate emissions of CO_2 per km traveled, with an average value of 0.144 kg km^{-1} for vehicles powered by ethanol and 0.207 kg km^{-1} for vehicles powered by gasohol. The flex vehicles powered by ethanol had an average emission of CO_2 of 0.150 kg km^{-1} and by gasohol of 0.191 kg km^{-1}.

METHODS

As the study is addressed to the expansion of the Viracopos International Airport, it was defined three periods for the calculation of the aircraft emissions methodology: beginning of the construction for the expansion in 2008, the year of 2012 (considered the current stage) and the year of 2018 which is the time foreseen for the completion of early-stage works according to the Master Plan from the Viracopos International Airport (NACO, 2013). For the inventory of emissions by aircraft, it was accounted the contribution of passenger´s travel and cargo transportation.

Intended for the application of emissions by vehicles, it was defined two periods: 2012 representing the current situation and the year of 2018 as explained above.

Aircraft emissions inventory

To estimate the emission of pollutants by aircraft for the transport of passengers, it was necessary to review the annual aircraft movements (landings + departures) for the years 2008 and 2012, obtained in the Statistical Yearbook of 2012 (INFRAERO, 2013). The emission factors are different for middle-age fleet and aging fleet, as shown in **Table 1**.

An investigation of the average age of passenger´s aircraft fleet at the Viracopos International Airport showed that the circulating fleet is less than 10 years old. Additionally, a new airline initiated the majority of the flights at the Viracopos Airport with an average age fleet of three years. Thus, for the calculation of emissions from aircraft in passenger´s transport at 2008 and 2012 it was used the emission factors for a middle-age fleet according to the IPCC method. For the future scenario (2018), it was found projections from the Environmental Impact Report from Viracopos Airport (Walm, 2009) and from the Metropolitan Agency of Campinas (AGEMCAMP) to evaluate the emissions.

Table 1. Average emission factor (in kg/LTO) for middle-age fleet and aging fleet (IPCC, 2000)

	Emission Factor						
Domestic flight (kg/LTO)	SO_2	CO	CO_2	NOx	NMHC*	CH_4	N_2O
middle-age fleet	0.8	8.1	2,680	10.2	2.6	0.3	0.1
aging fleet	1	17	3,150	9	3.7	0.4	0.1
International flight (kg/LTO)	SO_2	CO	CO_2	NOx	NMHC*	CH_4	N_2O
middle-age fleet	2.5	50	7,900	41	15	1.5	0.2
aging fleet	2.4	101	7,560	23,6	66	7	0.2

*NMHC = Non-methane hydrocarbons

Table 2. Summary of the number of aircraft (takeoffs and landings) to the Viracopos International Airport - SP considering a variation of 8% (plus or minus) on 2018 forecasts

	Category of flight	2008	2012	2018	
				% (-)	% (+)
Total of aircrafts	*Domestic*	19,266	103,071	104,700	122,427
	International	7,100	8,656	64,231	75,106

Table 2 shows the aircraft numbers (takeoffs and landings) used to estimate the emission factor from the transport of passengers by **Eq. (2)**.

For the cargo transportation, it was not possible to obtain the annual movement of aircrafts due to the lack in data dissemination. Thus, to estimate the emission of pollutants by this category of flight, it was used the loaded data carried in 2008 and 2012. Moreover, for the year of 2012, it was possible to use the Integrated System of Civil Aviation Information (SINTAC) to filter the movement of cargo aircraft to and from the Viracopos Airport and their models. This procedure was not possible to implement with the 2008 data and there was no detailed forecast for the year 2018. As the analysis period is considered short, it was believed that no significant renewal of the aircraft models would occur. From the information obtained by the SINTAC, three models of aircraft were used in 2012 in 90% of cargo transport flights.

As the cargo transportation by aircraft is totally related to the monetary question, it is not advantageous to allow a plane to travel with loads quite below the maximum capacity. Thus, it was extrapolated that mostly aircrafts use their maximum capacity for cargo transportation. The data of transported cargo was made both for 2008 and 2012 through INFRAERO data reported by the System of Air Cargo Management (SIGCA, 2014).

With an increase of 24% in cargo transportation from 2008 to 2012, this same growth percentage was applied to the cargo quantity transported as a projection for the year of 2018. In addition, it was applied the minus and plus growth scenarios in the cargo projection made by NACO to obtain a margin of error around the estimated value, since this value is not absolute. The investigation of the average age of the aircraft fleet was also carried with the cargo aircrafts and it was found that this is an aging fleet.

Within all these workarounds, it was possible to estimate the movement of aircrafts at the Viracopos International Airport and the corresponding emission factor was applied for each year of the study according to the IPCC methodology previously described.

Vehicles emissions inventory

The estimated GHGs emission by vehicles was performed using microsimulation experiments with the help of the Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks software (AIMSUN® version 8.1, Catalonia – Spain). The simulation experiment was realized in two phases: one for the stage before the expansion of the airport (2008) and another for the first stage of the expansion (2012). Therefore, supporting data was necessary such as the road basis of the MRC, the project previous to the expansion of the Viracopos Airport (from AGEMCAMP) and the plan of the first stage of airport expansion (NACO, 2013).

With the help of ArcMap® software (version 9.3), the road base of the MRC was clipped by selecting only the surroundings of the airport and then the plans were georeferenced according to this new base. For the modeling of the pathways in the AIMSUN® software, in addition to the mentioned data, information about the number of tracks and the direction and number of connections were also provided by Google Maps® and Google Earth®.

Figure 1 shows the location of the Viracopos International Airport in São Paulo – Brazil and, in zoom, the road network around the Airport in the pre-expansion stage.

The Statistical Yearbook provides real data about passengers number in 2012 and at the peak-hour with around 2,156 of passengers loading and 2,004 unloading at that time (INFRAERO, 2013). The input and output movements of the roads were calculated with the number of passengers at the peak–time; accompanying people (it was assumed that there will be 0.5 accompanying for each passenger at the time-peak, considering the contribution of the companion in only one trip); airport staff (it was considered to be one person every 250 passengers annually and the hourly contribution to the terminal access flow was calculated assuming the arrival or departure of half of these employees in 6 hours); and the visitors (number of visitors was adopted as 10% of the airport employees and their hourly contribution is the total of those visitors divided by four, which is equivalent to two trips, one way and another back, distributed in 8 hours) (ICAO, 2011).

The percentages of transport modes used by those who attend the airport can be distributed by the number of vehicles who enter and leave the system and the occupancy rate adopted by the type of modal. This information is presented in **Table 3**.

Thus, the flow entry time and system output for each type of modal was calculated as the product of the number of people in the modal divided by the percentage of occupancy for this transportation.

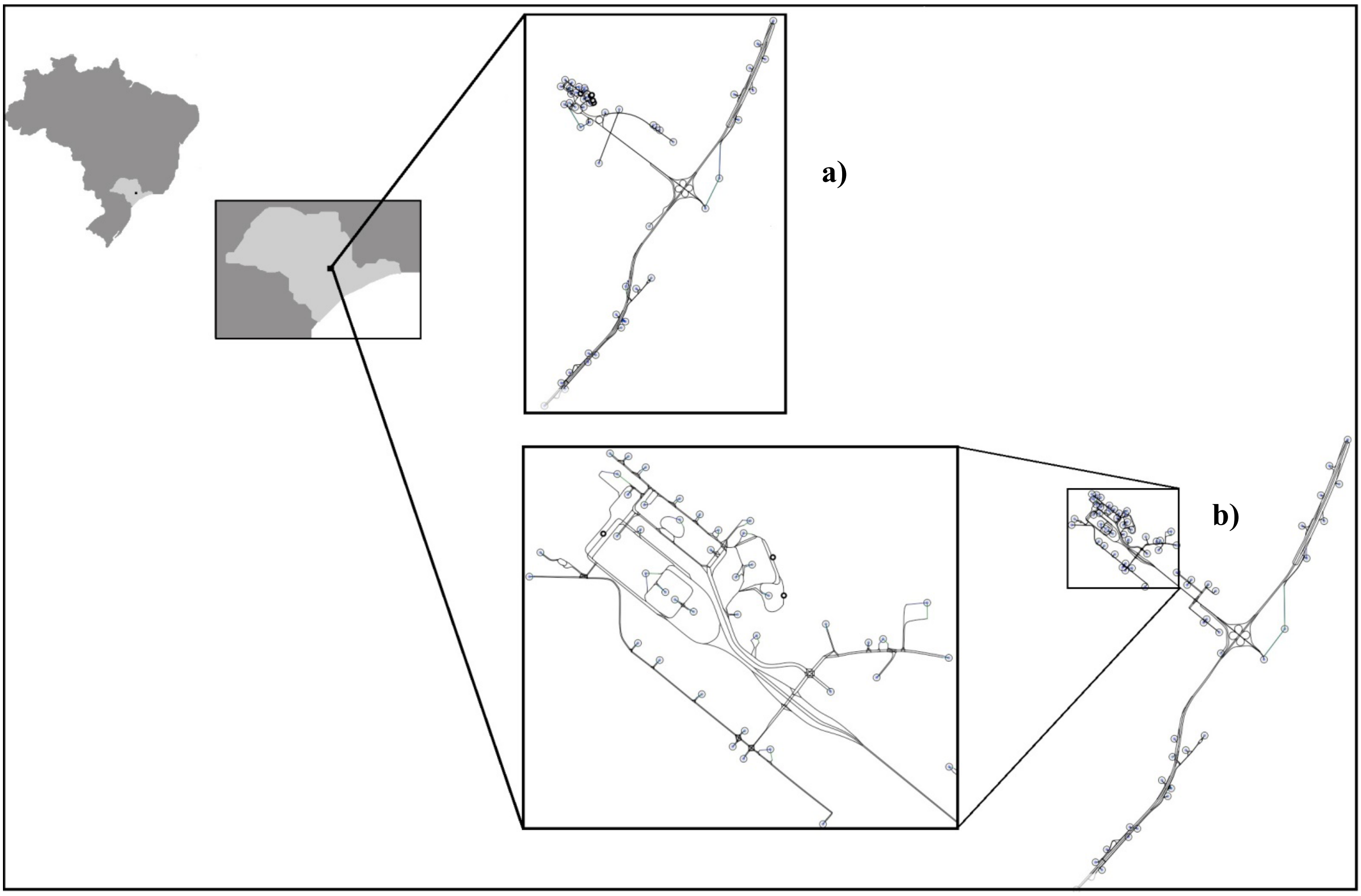


Fig. 1 Map of Brazil highlighting the state of São Paulo and the Campinas region where the the Viracopos International Airport is located. In detail a) road network before the airport expansion; b) the road network project (after the expansion of the airport) emphasizing the amplified area inside the Airport.

Table 3. Hypothesis of modal distribution through people attending the Viracopos International Airport and the occupancy rate adopted by the each type of modal (ICAO, 2011; Weigang & Alves, 1997)

Demand	Distribution by modal		
	Car	Taxi	Bus
Passengers	0.5	0.4	0.1
Accompanying	0.7	0.0	0.3
Airport staff	0.4	0.0	0.6
Visitors	0.5	0.1	0.4
Occupancy rate by type of modal	2	1.2	15

The simulation for estimating the emission of pollutants in the first stage of the expansion of the Airport was performed using sensitivity scenarios considering low, medium and high vehicle traffic to the new road network inside the airport.

In the microsimulation it was also inserted the public bus lines, the shuttle buses (parking-airport) and the taxis, only changing the path inside the airport because of the modification of the roadway network due to the expansion plan.

After entering all the data into the AIMSUN® software, 30 replications of microsimulations were realized for each scenario. As an output from the microsimulations it was obtained the emission results for the main GHGs estimated for 2012 and for each scenario for 2018. The AIMSUN® software is Spanish and does not use emission factors for ethanol vehicles – working only for vehicles with gasoline and diesel. Thus, the software emission results do not represent the Brazilian reality (predominantly flex cars). Despite this limitation, the results obtained were used for comparison in the estimation of emissions among the proposed scenarios.

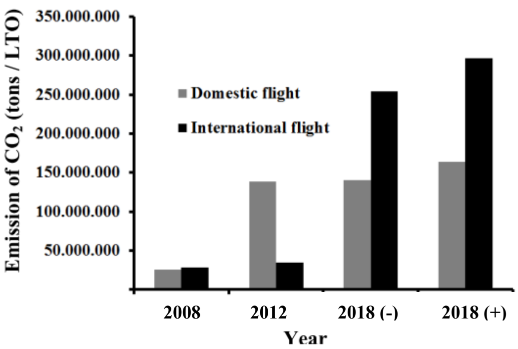
RESULTS AND DISCUSSION

From **Table 2** it was possible to estimate the air pollutants emissions for the transport of passengers at the Viracopos Airport. The number of aircraft is related to the number of cycles (LTO), or the number of takeoffs and landings. **Table 4** summarizes the numbers of cycles calculated from the number of aircraft and **Fig. 2** shows the emissions (in kilograms per cycle LTO) summation for domestic and international flights for each studied situation (2008, 2012 and 2018 scenarios).

Table 4. Estimated emissions of pollutants from passengers transportation on aircrafts at the Viracopos International Airport – SP (kg / LTO), considering a variation of 8% (plus or minus) on 2018 forecasts

Year	Category	Annual emissions (kg/LTO)						
2008	*Domestic*	7.706	78.027	25.816.440	98.257	25.046	2.890	963
	International	8.875	177.500	28.045.000	145.550	53.250	5.325	710
2012	*Domestic*	41.228	417.438	138.115.140	525.662	133.992	15.461	5.154
	International	10.820	216.400	34.191.200	177.448	64.920	6.492	866
2018 (-)	*Domestic*	41.880	424.035	140.297.925	533.970	136.110	15.705	5.235
	International	80.289	1.605.779	253.713.126	1.316.739	481.734	48.173	6.423
2018 (+)	*Domestic*	48.971	495.828	164.051.802	624.376	159.155	18.364	6.121
	International	93.883	1.877.654	296.669.358	1.539.676	563.296	56.330	7.511

a)



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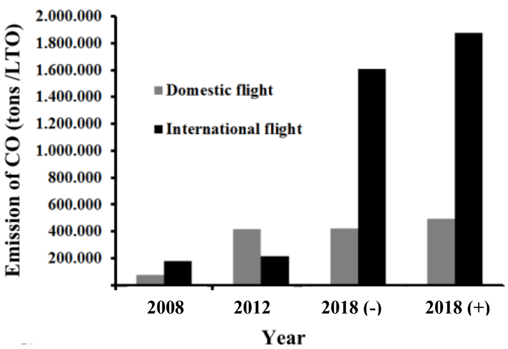

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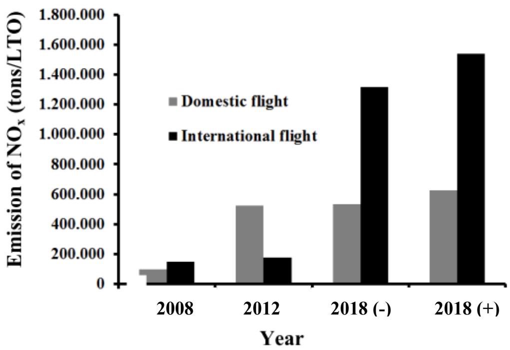

Fig. 2 Pollutants emissions related to passengers transportation by aircrafts per year At Viracopos International Airport (domestic and international flights by each scenario) in tons / LTO: A) CO_2; B) CO; C) NO_x.

Analyzing the results for the domestic flights, the NO_x emission is higher than the CO amount, but for international flights CO emission is greater than that of NOx. This fact is due to the different emission factors adopted for domestic and international flights, once the type of aircrafts used in each category of flight is different and has typical motor efficiencies.

It was observed an increase in the pollutants emissions for domestic and international flights between the years 2008 and 2012. This can be explained by the increase of 6 times on domestic flights and 1.5 times on international flights at the Viracopos Airport. Both for the low sensitivity scenario in 2018, 2018 (-), as for the high sensitivity scenario, 2018 (+), it was perceived that despite the projections assume that there will be an increase in the number of domestic flights superior to the international ones, the estimated emissions does not follow the same profile. It was observed that emissions from international flights are higher than those presented for domestic flights. These results are related to the emission factors used for these types of aircrafts which present greater emission factors than the typical aircrafts for domestic flights.

For cargo transportation, it was possible to estimate emissions from air transport loads with **Eq. (2)** and also considering the number of cycles from the number of aircrafts. **Table 5** summarizes the results for cargo transportation in the studied years and scenarios and **Fig. 3** shows the emissions (in tons/LTO) for CO_2 (**Fig. 3a**) and SO_2, CO, NO_x, NMHC and CH (**Fig. 3b**) for the three years analyzed.

Both for passengers and cargo transportation, it is noticeable the increase in the estimated emissions. This comes across with the growing demand of the Viracopos International Airport. The expansion of the airport was firstly motivated on increasing passenger´s demand, which can also be related to higher growth in emissions from this category of air transport. Unlike what was observed for passenger´s aircraft emissions, the emissions from cargo transportation did not differ

Table 5. Estimated emissions of pollutants from cargo transportation on aircrafts at the Viracopos International Airport – SP (kg / LTO), considering a variation of 8% (plus or minus) on 2018 forecasts

Year	LTO	Annual emission (kg/LTO)						
2008	1.450	3.479	146.400	10.958.220	34.208	95.667	10.147	290
2012	1.306	3.133	131.856	9.869.580	30.810	86.163	9.139	261
2018 (% -)	1.474	3.538	148.874	11.143.440	34.786	97.284	10.318	295
2018 (% +)	1.584	3.800	159.934	11.971.260	37.371	104.511	11.085	317

significantly between the three years analyzed (including the different scenarios). Thus, considering the boundary conditions that were adopted, it is not possible to say that there will be a significant increase in these types of emissions.

For assessing the contribution of land transportation, it was realized 30 replications of the microsimulation experiment considering the contribution of the emissions of pollutants from cars, taxis and buses. For the year 2012 it was considered as input to the AIMSUM® software the current road network of the airport and for the scenarios of 2018 (high and low sensitivity) it was regarded the designed network for the expansion of the Viracopos Airport. **Figure 4** shows the total annual emission of pollutants considering each proposed scenario.

Seeing the considered scenarios, as might be expected, there is a tendency of increase in emissions between the present and the future situations, both for the low and high sensitivity experiments. For the CO_2 emission, a conversion factor was established by Duarte & Paiva (2013) in order to bring the results to the Brazilian representativeness. It is noteworthy that these conversion factors are only available for vehicles with alcohol, gasoline and flex, what just allowed the analysis of the results for cars and taxis.

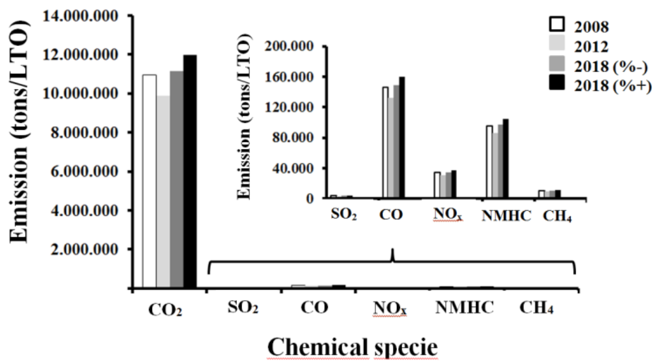

Fig. 3 Annual emissions for cargo transportation from aircrafts in tons/LTO: A) CO_2; B) SO_2, CO, NOx, NMHC and CH_4.

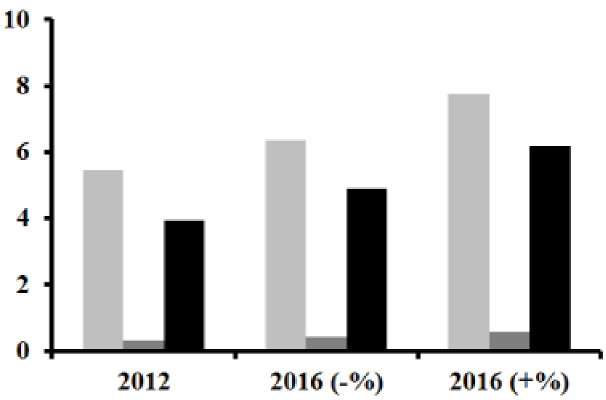

Fig. 4 Annual emissions of pollutants from land transportation at the Viracopos Airport: a) CO; b) NO_x, VOCs and PM.

Table 6. Total CO_2 emissions in one hour (in kg) for air transportation (sum of passengers and cargo) and for land transportation (sum of cars and taxis) at the Viracopos International Airport – SP

Year	Emission of CO_2 in one hour (kg)	
	Air transportation	Land transportation
2012	20,796	2,587
2018 (+)	46,251	3,100
2018 (-)	53,960	3,903

Table 6 summarizes the CO_2 emissions per hour (in kg) for air transportation (passengers and cargo) and for land transportation (cars and taxis) at the Viracopos International Airport, considering the years of 2012 and the low and high sensitivity scenarios for 2018. Note that in the estimative of emissions from the land transportation it was excluded from the calculation the contributions from diesel vehicles as buses, transport cargo cars and the machinery for operations inside the airport. Thus, this type of emissions tends to be even higher than it was scaled in the present work.

It is possible to verify that there was an increase in the emissions from all periods, justified by the increased demand from the airport expansion. The increase between 2008 and 2012, 2012 and 2018 (-) and 2012 and 2018 (+) was, respectively, 181%, 122% and 159%. At a first glance, it can be mean that the CO_2 contribution from the aircrafts tends to be higher than the output obtained by land transportation. However, this result cannot be considered conclusive due to different boundary conditions adopted for each type of modal studied.

CONCLUSION

The case study of the expansion of the Viracopos International Airport has shown the importance of considering emissions from air transportation due to expectancy of growth of this sector in the Metropolitan Region of Campinas. In addition, because the airport is a trip generator center, is also of huge importance to consider pollutants emissions from land transportation.

The work allowed studying methodologies for estimating pollutants emissions by aircrafts and strength the knowledge of the AIMSUN® software to estimate emissions by vehicles. These evaluations were made by adopting initial boundary conditions due to difficulties in obtaining data. With the present work it was possible to observe that both air and land transportation present a trend to increase pollutants emissions due to the expansion of the Airport.

As a final statement, it is important to note that the results can be the basis for the establishment of pollutants emission management plans' for the competent entities and the proposal of more targeted and effective procedures to minimize emissions of GHGs by type of source.

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