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UAV influence in the emissions of airborne cargo transportation

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Abstract

The global market of unmanned aircraft has been strongly growing for the past years and will remain doing so in the future. At the same time, the air traffic from cargo transportation has recovered from the world economic crisis and is experiencing further growth. Given the multiple advantages that UAVs present for cargo transportation, a number of companies have started to study their use for shipping of packages and mail, both in short- and long-range routes. During recent years, international organizations have undertaken the task to create regulations and sanction the current and future merger of manned and unmanned air traffic. The effects of this trend are still unclear, and so are the implications of replacing nowadays cargo transportation with UAVs.
In this work, the market of manned commercial transportation in the European Union is presented. That includes routes, schedules, mission structure, and environmental impact. Starting from the current situation and taking in account the future trends of air cargo, the impact that UAVs will have in air cargo transportation is studied in various scenarios. Including different UAV and environmental regulations, speed of implementation, or mission strategies like diurnal vs nocturnal cargo distribution.

1. Introduction

During the last years, the world market of unmanned aircraft has experienced strong growth. A number of organizations and institutions have forecasted a similar trend for the next decade [1–4]. It is expected to "total $88.3 billion in the next decade" [5]. The impact that unmanned aircraft have had in the economy and society has been equally strong [6–9]. This rapid growth has not been without inconveniences. The assimilation of Remotely Piloted Aircraft Systems (RPAS) by companies and population has been faster that the regulation process undertaken by public institutions. A number of stakeholders emitted reports and opinions and started initiatives on the subject [10–14]. However, more recently, legal foundations have been stablished by regulatory institutions [15–18].

Even though their use started off in the military [19,20], they are nowadays involved in every side of civil life, such as terrain mapping and observation [21,22], scientific missions [23] or wildlife preservation [24]. One of the civil applications of Unmanned Aerial Vehicles (UAV) is cargo/freight transportation. The air freight market has recovered from 2008's world economic recession, however at a slower pace than passenger transportation [25,26]. Air cargo transportation represents around 1% of the total global cargo transportation in weigh, but around a 35% of the value [27,28]. There are studies and patents aimed at the use of UAV instead of manned aircraft or land vehicles [29–32], and the public opinion shows acceptance of this usage [33,34]. The use of air vehicles could remove traffic congestion

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generated by the increasing home package delivery from recent years [35]. In addition, UAV could reduce the need for manhours, work 24 hours a day, 7 days a week, and reach areas that have difficult access by land. Several companies are starting to test new systems related to home delivery, such as Amazon's Prime Air [36] and Google's air freight company [37].

This increasingly widespread use of UAV presents a number of challenges and questions to the current status-quo. The introduction of RPAS and other UAV in the air space requires of a fundamental evolution of the current Air Traffic Management (ATM) strategies and approaches [38–40]. In addition, the particular environmental effects of a possible shift of air cargo transportation towards an unmanned environment are difficult to forecast and estimate. For these reasons, in this work, we model, size, and study the impact of the future of UAV cargo transportation in the European Union.

We present here a forecast of several possible scenarios of noise and pollutant emissions (carbon monoxide, CO; nitrogen oxide, NO_X; hydrocarbures, HC; and carbon dioxide, CO_2) until 2040. To study the environmental impact and emissions generated in 2040, we gathered information about the current situation and the predicted evolution of airborne cargo traffic in the future. Then, we proposed alternative scenarios to which the current cargo fleet may evolve. Finally, we compared the noise and pollutant emissions resulting from each scenario.

2. Model UAV for cargo transportation

In order to be able to compare the current performance, emissions and general climate impact of airborne cargo it is necessary to previously define the RPAS fleet that could potentially replace the aircraft that currently transport it. To define such an aircraft there are several elements that must be taken into account:

Cargo is usually defined by dimension and size. Therefore, any UAV that is intended to be used as an alternative to regular aircraft shall be able to carry, at least, a single package. These variable widely vary and can range from a few grams and cubic centimeters to carry a single envelope, to about one or two tons and a few cubic meters when transporting a car. FedEx and USPS provide information regarding these variables [41,42], which set the maximum weight at around 1100 kg, and the maximum volume at around 2.4 m^3.Given the cost of air transportation, heavier and/or bigger objects tend to be shipped by surface. Cargo that is not very valuable or does not pose tight time-constraints tends to be shipped also by surface transportation. This particular characteristics have led airborne cargo to present a higher value-to-weight ratio than that shipped by other means.

The other main variable that defines air cargo is the distance between the point of departure and destination. We gathered data from Eurocontrol DDR2 Web Portal [43] regarding air cargo traffic between European airports following the STATFOR Market Segmentation Rules [44]. The average distance traveled by an aircraft from departure to destination was approximately 2377 km. While these values provide an estimation of the current situation of cargo transportation, the possible outcomes of the UAV development during the following years could be very disrupting. Currently, batteries present limitations versus fossil fuels when comparing airplane range and payload, but developments in quantum batteries [45] could change that in the following decades. There are two main variables that are susceptible to change: size, and power source. These two variables also have a large impact on the noise and pollutant emissions of the aircraft. To estimate their impact, we considered three possible combinations of these factors.

2.1. Small fuel-powered UAV

Pollutants

While the previously mentioned requirements are within reach of current UAV, only military RPAS hold similar ranges while being able to carry a payload of that weight at the moment. As mentioned in the introduction, a few companies are testing home-delivery UAV at the moment but, in addition, several companies are developing larger cargo UAV, such as Volans-i [46] and Star UAV System's AT 200 [47], which is based on the PAC P-750. This last UAV's range and payload are very similar to the estimations presented before. Therefore, the estimated fleet will be based upon this aircraft. The PAC P-750 carries a Pratt & Whitney Canada PT6A-34 engine, whose emissions for a landing and take-off cycle (LTO) can be found in the European Environmental Agency's Emission Inventory Guidebook [48]. The values provided in the previous reference correspond to CO, CO_2, NO_X and HC emissions for flying distances of 125, 250, 500 and 750 km. To estimate a kilometric emission of each of the pollutants during a flight, we calculated linear regressions with the distance of the flight. These regressions are shown in equations 1-4. Table 1 shows estimated emission values for flights of 500, 1000, 1500 and 2500 km.

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$$NOX\ [kg] = 0.2145 + 2.923 * 10^{-3} * distance\ (km) \tag{1}$$

$$HC\ [kg] = 0.0212 + 1.001 * 10^{-4} * distance\ (km) \tag{2}$$

$$CO\ [kg] = 0.3371 + 2.0093 * 10^{-3} * distance\ (km) \tag{3}$$

$$CO_2\ [kg] = 110.3 + 1.6273 * distance\ (km) \tag{4}$$

Table 1: Estimated emissions for a standard cargo UAV [kg].

	500 km	1000 km	1500 km	2500 km
NO_X	1.676	3.1375	4.599	7.522
HC	0.07125	0.1213	0.17135	0.27145
CO	1.34175	2.3464	3.35105	5.36035
CO_2	923.95	1737.6	2551.25	4178.55

Noise
Regarding noise emissions, PAC P-750's EASA Data Sheet for Noise [48] shows a noise of 86.8 dB during take-off.

2.2. Small electrically powered UAV

Pollutants
Aircraft that are powered with electrical engines do not emit pollutants during flight.

Noise
The noise generated by a static aircraft that is electrically powered will be that of its propeller. To estimate this noise for a small UAV, we studied the characteristics of Pratt & Whitney Canada's PT6A-34 engine, as an electrical engine should deliver the same performance as its fuel-powered equivalent. The PT6A-34 from PAC P-750's EASA Data Sheet for Noise [48] used a HC-B3TN-3D/T10282NS+4 propeller [49]. Using the equations for propeller noise estimation from Hamilton Standard's [50], we estimated that the propeller, in the conditions under which PAC P-750's EASA Data Sheet for Noise measurement were performed, produces approximately 82 dB.

2.3. Large fuel-powered UAV

Pollutants
These aircraft are assumed to be nowadays planes that have been upgraded so that it is possible for them to fly without a pilot. Therefore, he pollutant emissions generated by large fuel-powered aircraft have been estimated to be equal to those from manned aircraft, as the emissions are unrelated to the existence of a crew.

Noise
In a similar manner to pollutants, the noise emissions have been considered to be equal to the manned counterparts of these aircraft.

3. Emissions

We gathered information about the emissions of pollutants (CO, CO_2, NO_X and HC) and noise generated in LTO by cargo aircraft at European airports during an average week from 2008 to 2018 and forecasted their evolution until 2040. The emissions were estimated to be a 254% of those from year 2018, as the cargo RTK (Revenue Tons Kilometers) are expected to grow by a 4.2% yearly average until 2040 [26]. To estimate the cargo transported by each flight we used a load factor of 40-50% [51].

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3.1. Pollutants

Carbon monoxide, nitrogen oxide and hydrocarbure emissions are known to primarily affect the areas where they are emitted. For this reason, we focused on the emission of these pollutants during take-off and landing and their trend from 2003 to 2018. We forecasted their growth until 2040 and studied their impact at each airport. This forecast is the baseline scenario against which we compared alternative evolutions of the cargo transportation fleet and assumes that the transportation is carried out by a similar fleet. The only difference between 2018 and 2040's fleet is their size.

We estimated airborne cargo fleet emissions with five different scenarios, all which consider a 4.2% yearly growth of the RTK until 2040:

- Scenario 1 (baseline): As mentioned before, the baseline scenario considers an unchanged cargo fleet. This scenario assumes no technological advancement until 2040, but an increase of the number of aircraft.
- Scenario 2: In this case, aircraft that travel less 1000 km are replaced by a set of fuel-powered UAV delivering the same RTK. As the higher number of aircraft will more easily allow an "on-demand" transportation of goods, the UAV are assumed to have a 0.9 load factor.
- Scenario 3: This scenario is the same as Scenario 2, but the UAV are assumed to have electrical propulsion.
- Scenario 4: All flights under 5000 km are performed by fuel-powered UAV.
- Scenario 5: As a combination of Scenarios 3 and 4, in this scenario, all flights under 2500 km are performed by electrically powered UAV, while the flights between 2500 and 5000 km are performed by fuel-powered UAV.

3.1.1. Pollutants with local effect

Carbon monoxide

Figure 1 presents a comparison of the total emission emissions of carbon monoxide trends as forecasted in each scenario during an average week of year 2040. While Scenario 1's curve shows the growth in the emissions as motivated by the increased RTK, Scenarios 2-5's graphs take into account a gradual shift from Scenario 1's transportation paradigm towards each scenario's final situation. In other words, the trend lines of all scenarios start, in year 2017, considering that all the transportation is being performed by conventional aircraft. As years pass, the transportation is performed by a fleet increasingly closer to each Scenario's final situation in 2040, which is the one defined in the previous section. The rationale to draw them this way is that technology shifts are gradual. For instance, when considering Scenario 3, where flights under 2500 km are performed by electrical UAV, we assume that the actual percentage of electrical UAV used in 2017 for these flights will be 0% and will gradually increase up to a 100% in 2040. Among the five studied scenarios only Scenario 3 presents a noticeable reduction of emissions, and only to the levels from 2013. Scenario 5 maintains a level of emissions similar to the current one, while Scenarios 1, 2 and 4 predict their growth.

Results show that the baseline scenario the case with the highest emissions, followed by Scenarios 4, 2, 5 and 3, in that order. This are reasonable results, since the Scenarios including electric UAV are expected to have lower emissions. In addition, the intermediate situation of Scenarios 2 and 4 shows that the use of UAV by themselves, without improving the current technology, is positive. In these two scenarios there are two factors that define the end result: First, the number of flights when using UAV instead of a large aircraft increases, which is by itself more inefficient. And, secondly, the load factor of UAV is considerably higher. Results, in this, case show that the increased load factor of UAV outweighs the inefficiency of the higher number of flights. An interesting result is, however, that performing flights under 2500 km with UAV is more advantageous than performing flights under 5000 km with them.

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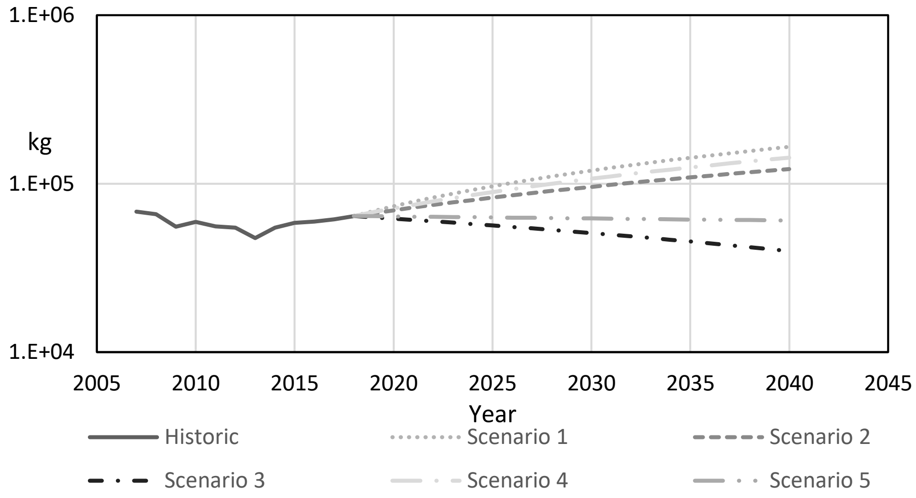

Figure 1: Emissions of carbon monoxide as forecasted in five different scenarios.

Figure 2 shows the emissions of carbon monoxide trends from 2007 to 2040 as forecasted in the five different scenarios previously introduced and divided by the RTK of each year. As in Figure 1, the trend lines in this figure are representative of the efficiency of the transportation. As a matter of fact, given that in the baseline scenario (Scenario 1), we assumed that the technology would not evolve, the kg to RTK ratio remains unchanged. The other four cases present kg/RTK ratios that decrease by up to around half an order of magnitude.

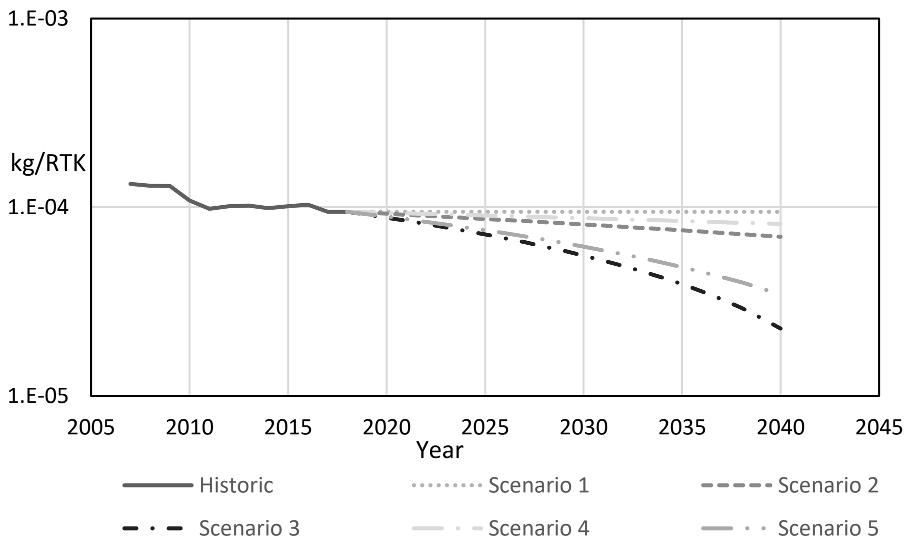

Figure 2: Emissions of carbon monoxide as forecasted in five different scenarios divided by each year's RTK.

Figure 3 presents maps showing the emissions of carbon monoxide forecasted, at each airport, in each scenario. Central Europe displays the highest concentration of emissions. A quick glance confirms the results shown in the previous graphs. As estimated in Figures 1 and 2, Scenarios 3 and 5 show lower emissions across airports.

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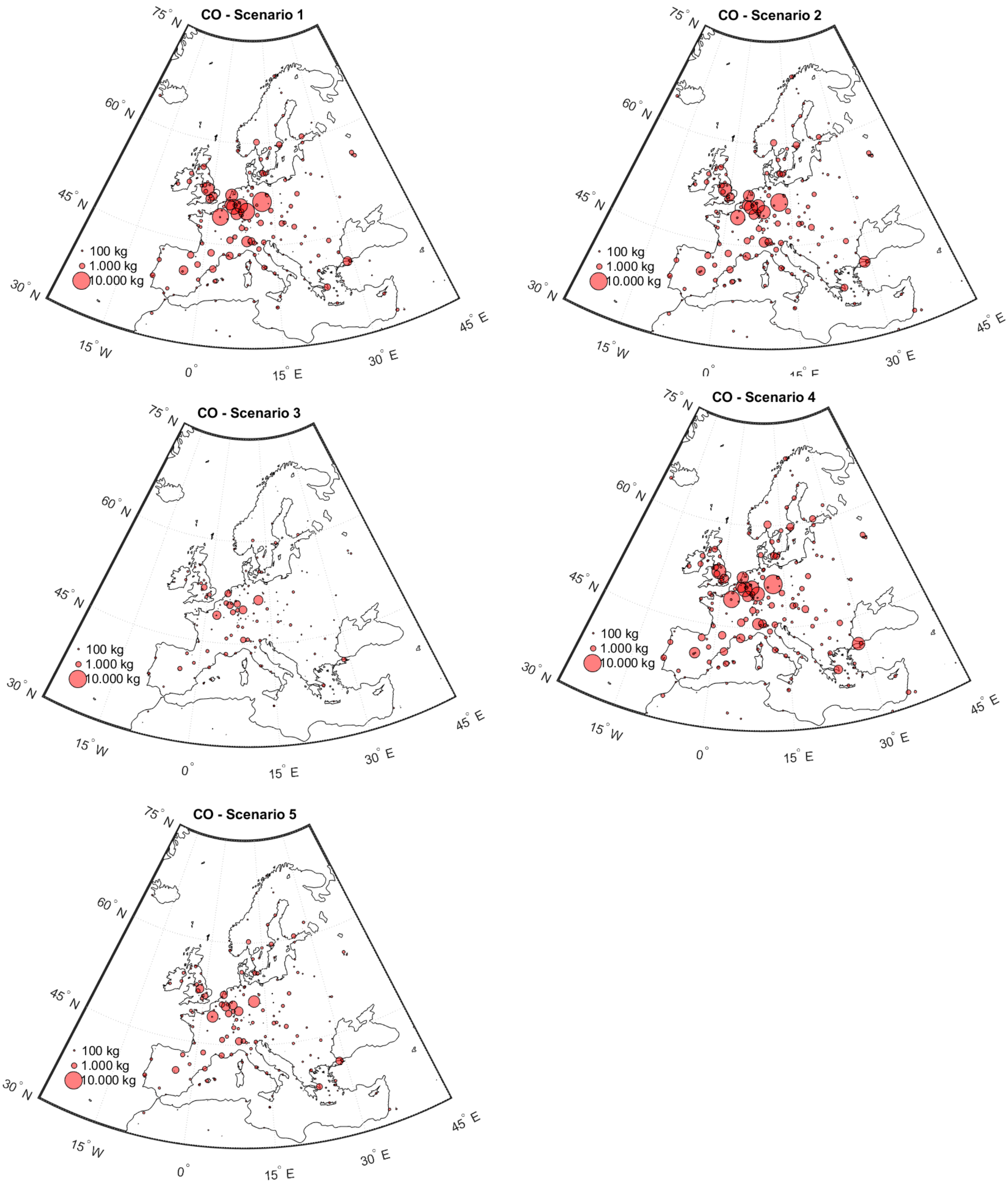

Figure 3: Maps of emissions of carbon monoxide at European airports as forecasted in each scenario.

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Nitrogen oxides

Figure 4 presents a comparison of the total emission emissions of nitrogen oxide trends as forecasted in each scenario. As expected, the behavior shown by the five trends is similar to that of the carbon monoxide emissions. A noticeable reduction of the emissions is shown in scenarios 5 and 3, which bring them close to the levels of 2013. The rest of the scenarios drive the emissions towards higher levels in the future.

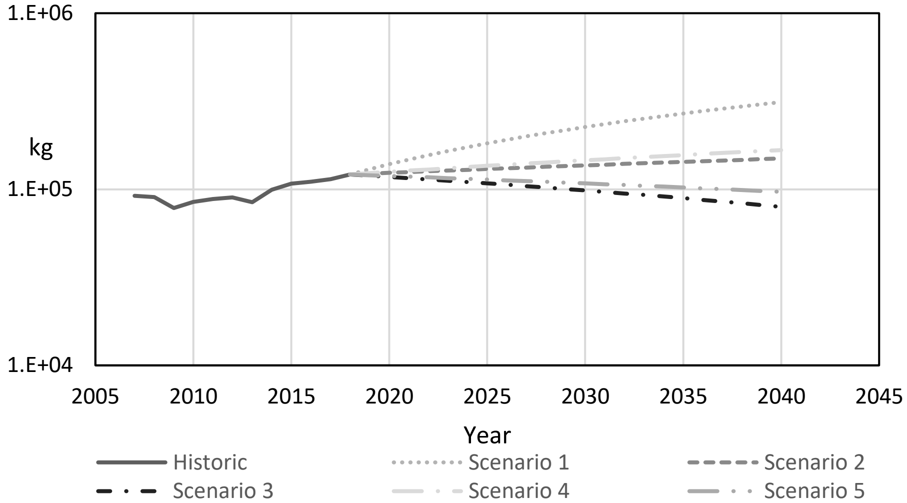

Figure 4: Emissions of nitrogen oxides as forecasted in five different scenarios.

Figure 5 shows the results from Figure 4 divided by each years RTK. As expected, the curve corresponding to the baseline scenario remains flat, while the rest of the scenarios predict improving ratios of emitted kg to RTK.

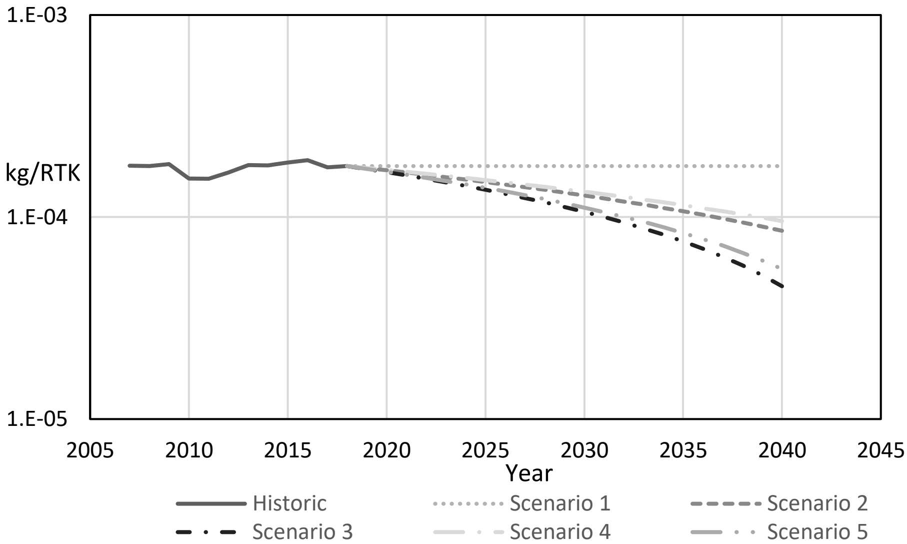

Figure 5: Emissions of nitrogen oxides as forecasted in five different scenarios divided by each year’s RTK.

Figure 6 presents maps showing the emissions of nitrogen oxides forecasted, at each airport, in each scenario. Scenarios 3 and 5 show lower emissions across airports.

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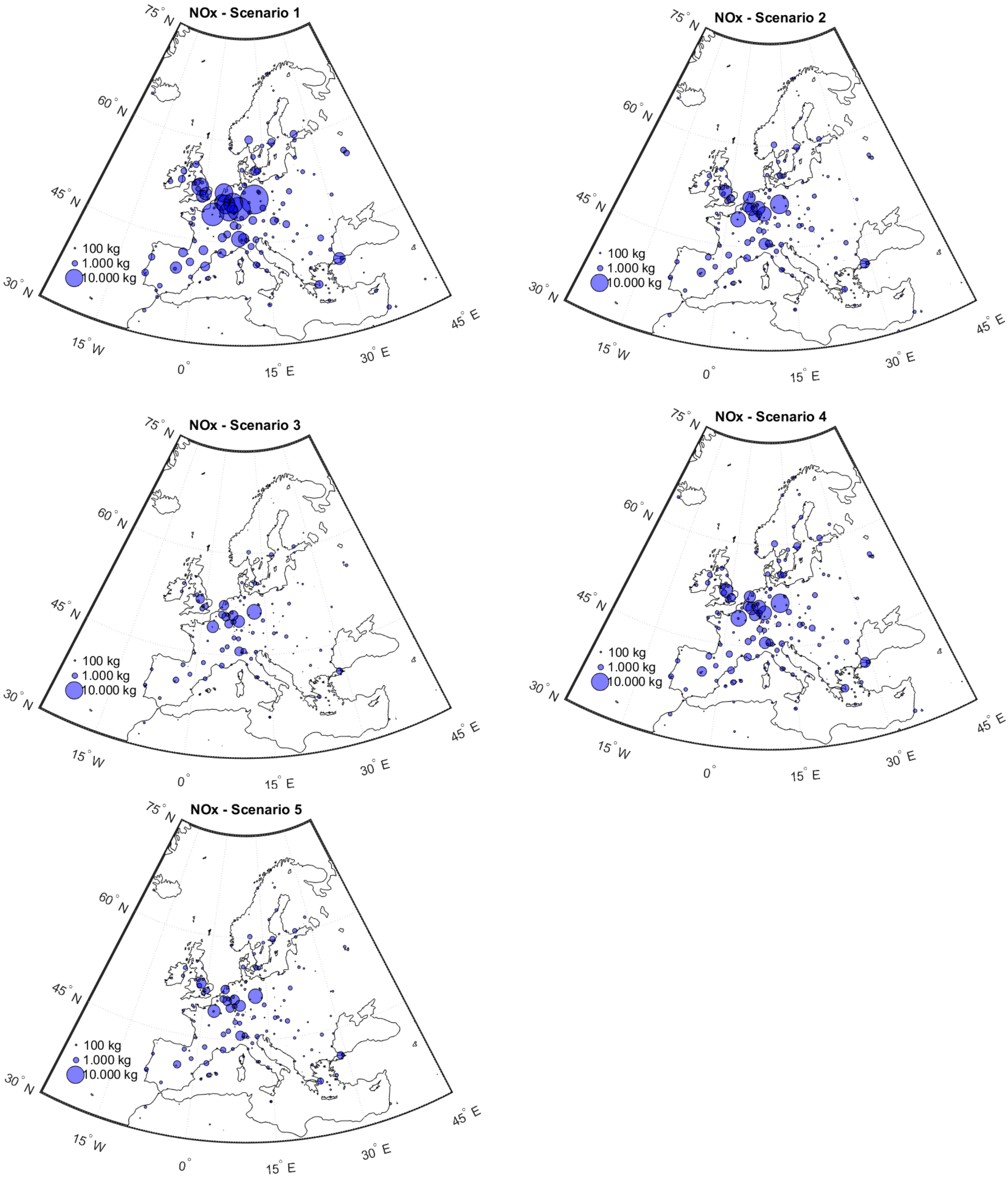

Figure 6: Maps of emissions of nitrogen oxides at European airports as forecasted in each scenario.

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Hydrocarbons

Figures 7 and 8 show the emissions of hydrocarbons and those emissions divided by each year's RTK respectively. Akin to carbon monoxide and nitrogen oxide, hydrocarbon emissions are lowered in Scenarios 3 and 5, and increase in Scenarios 1, 2 and 4.

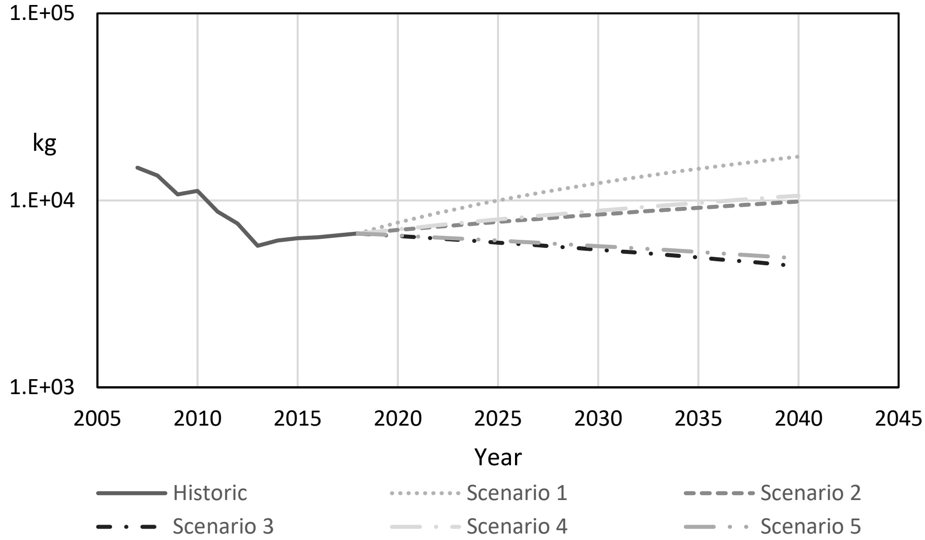

Figure 7: Emissions of hydrocarbons as forecasted in five different scenarios.

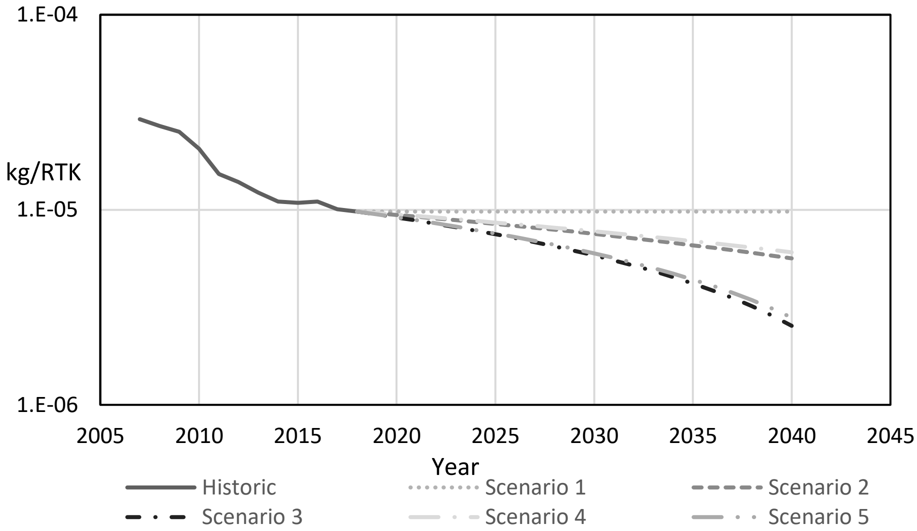

Figure 8: Emissions of hydrocarbons as forecasted in five different scenarios divided by each year's RTK.

Figure 9 displays maps with the emissions of hydrocarbons forecasted, at each airport, in each scenario. Akin to the carbon monoxide results, Scenarios 3 and 5 show lower emissions across airports. The reduced order of magnitude of hydrocarbon emissions as compared to those of carbon monoxide can also be seen in them.

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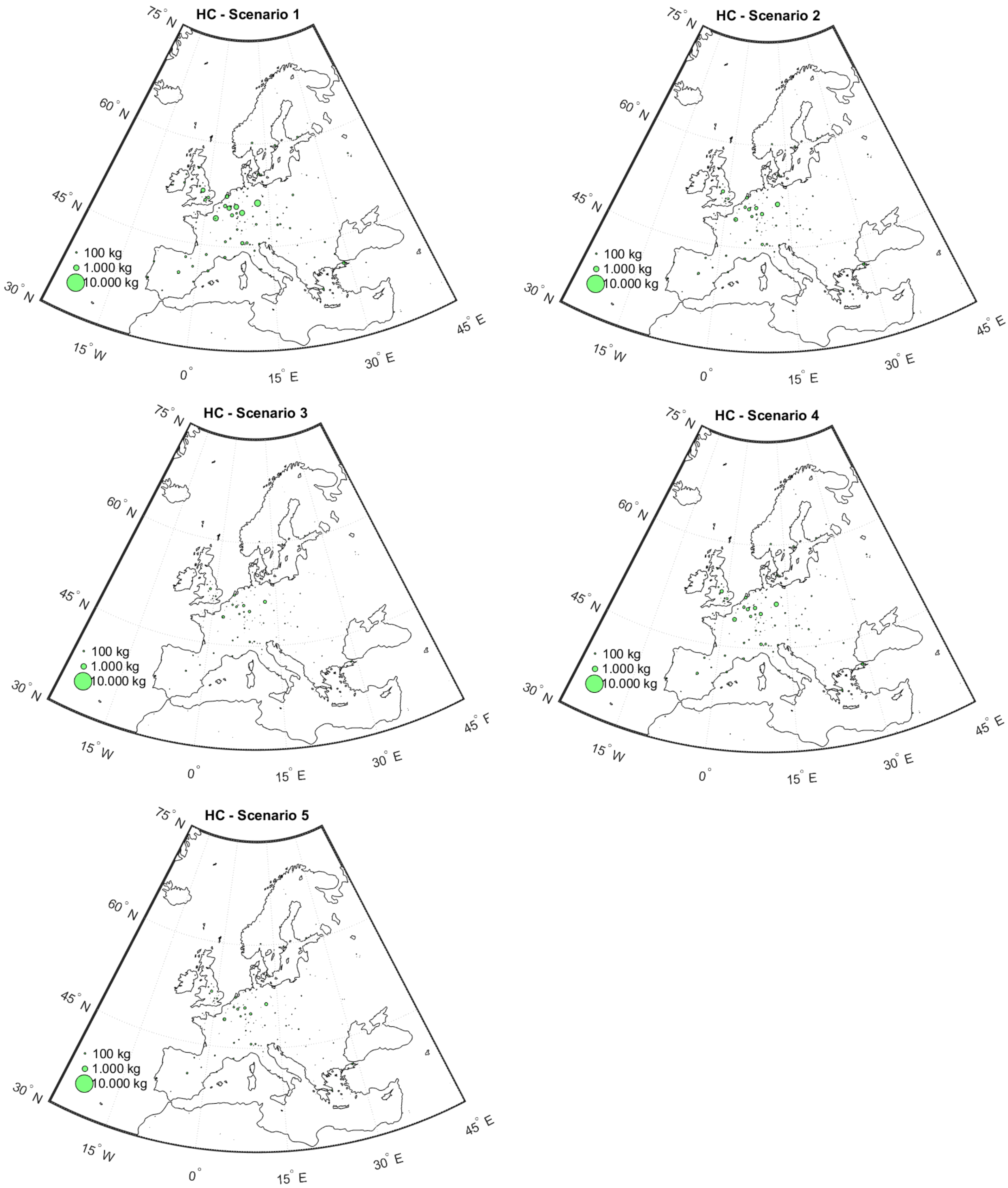

Figure 9: Maps of emissions of hydrocarbons at European airports as forecasted in each scenario.

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3.1.2. Pollutants with global effect: carbon dioxide

Unlike the pollutants from section 3.1.1, carbon dioxide emissions have a global impact. They affect global warming and climate change. Therefore, in this section, carbon dioxide emissions include the LTO cycle and cruise of the aircraft, including cruise. Figure 10 shows the emission trends and predictions from 2007 to 2040. As happened with the other pollutants, the lowest emissions were predicted in Scenario 3, which would take them to 2013 levels. The highest emissions, as expected, belong to Scenario 1. Contrary to the results seen in the previous section, Scenario 5 resulted in higher emissions than Scenario 2. As shown in the carbon monoxide results, only Scenario 3 presents lower emissions than the current ones.

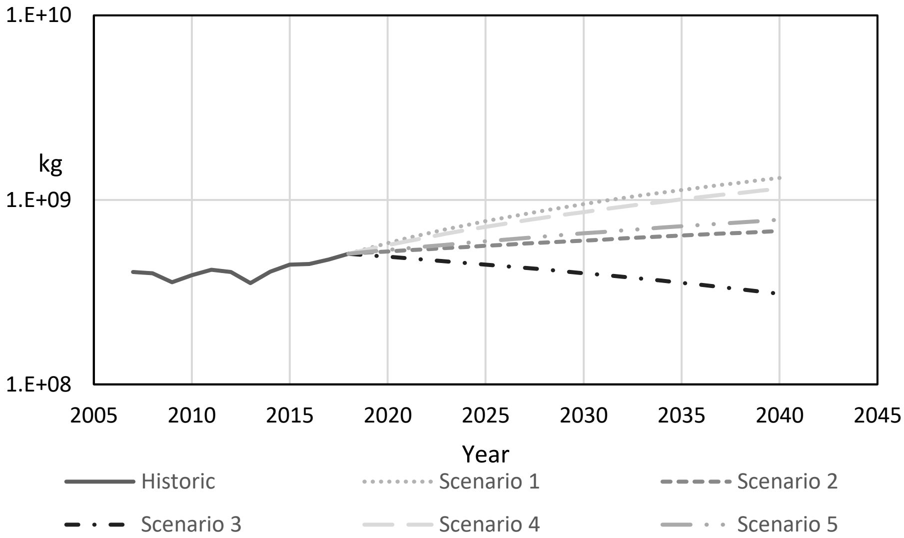

Figure 10: Emissions of carbon dioxide as forecasted in five different scenarios.

Figure 11 presents the kg of emitted carbon dioxide divided by the yearly RTK. Results show that Scenario 3 could reduce the CO_2 emissions by RTK by up to a 76%.

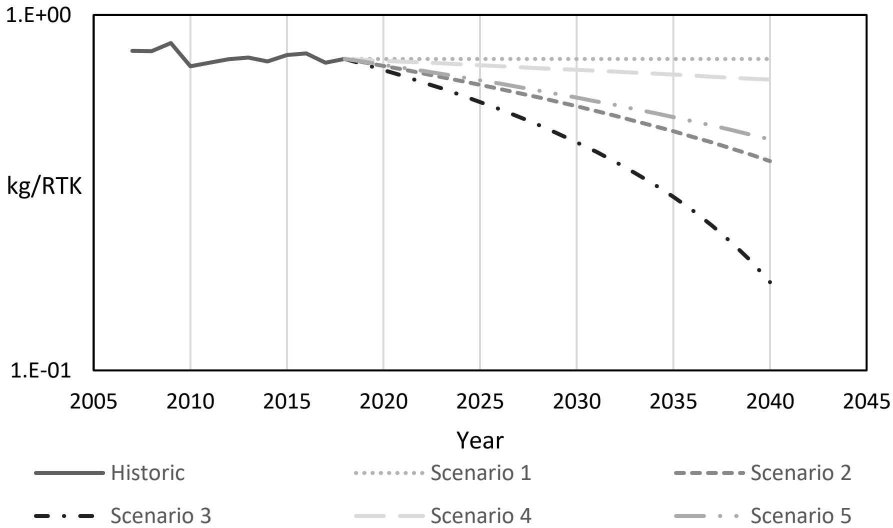

Figure 11: Emissions of carbon dioxide as forecasted in five different scenarios divided by each year’s RTK.

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3.2. Noise

We studied the noise generated from cargo flights at European airports throughout the day. The flights included in the study are the same as in Section 3.1. Akin to that section, the amount of RTK were forecasted from 2018's data with a 4.2% of yearly growth. Five different scenarios coinciding with the prior Scenarios 1-5 were studied. In addition, each scenario including UAV (Scenarios 2-5) was altered to consider a variation where the UAV flights are evenly spread throughout the day. That resulted in the following nine scenarios:

- Scenario 1 (baseline): As mentioned before, the baseline scenario considers an unchanged cargo fleet. This scenario assumes no technological advancement until 2040, but an increase of the number of aircraft.
- Scenario 2: In this case, aircraft that travel less 1000 km are replaced by a set of fuel-powered UAV delivering the same RTK. As the higher number of aircraft will more easily allow an "on-demand" transportation of goods, the UAV are assumed to have a 0.9 load factor.
- Scenario 2 - spread: This scenario matches Scenario 2, but the flights performed by UAV are spread evenly throughout the day.
- Scenario 3: This scenario is the same as Scenario 2, but the UAV are assumed to have electrical propulsion.
- Scenario 3 - spread: This scenario matches Scenario 3, but the flights performed by UAV are spread evenly throughout the day.
- Scenario 4: All flights under 5000 km are performed by fuel-powered UAV.
- Scenario 4 - spread: This scenario matches Scenario 4, but the flights performed by UAV are spread evenly throughout the day.
- Scenario 5: As a combination of Scenarios 3 and 4, in this scenario, all flights under 2500 km are performed by electrically powered UAV, while the flights between 2500 and 5000 km are performed by fuel-powered UAV.
- Scenario 5 - spread: This scenario matches Scenario 5, but the flights performed by UAV are spread evenly throughout the day.

Figures 12-15 show the noise generated from takeoff at the airports during day and night. Similar figures can be traced for landing. Figures 12 and 14 compare all nine scenarios while Figures 13 and 15 compare the baseline scenario to the two scenarios of each kind (non-spread and spread) with lowest noise, which pertain to Scenario 5. The figures represent the addition of all the noise emitted at each airport at the local time.

Due to the fact that noise is measured in EPNdB (Effective Perceived Noise in deciBels) and added together by the means of logarithms, two different graphs were chosen to represent the data: Figures 12 and 13 show the regular addition of the noise generated by each aircraft at each hour in local time. Figure 15, on the other hand, shows the logarithmic addition of such noise. Because of this, Figures 12 and 13 have a bias regarding the number of operations that produce the noise. For instance, two take offs taking place at the same time, that produced a noise of 80 dB would add up to 160, while the combined noise that they generated would only amount to 83.01 dB. In these figures, a flight generating 85 dB, that would amount to a higher noise, would show lower. Therefore, Figures 14 and 15 show differences strictly related to the noise, while Figures 12 and 13 include the number of operations.

Figures 12 and 13 show that higher peaks happen in the non-spread scenarios, the highest one being from the baseline scenario. Spreading the UAV operations lowers the higher peaks, even though it increases the level at the valleys. There is also a clear reduction from Scenario 1 to the other alternative scenarios. This reduction in noise can be also seen in Figures 14 and 15, where the reduction can be measured at almost 0.5-1 dB. Given the particularities of the noise addition, this measurement is not a perfect representation of the real situation at each airport, but an indication that, regardless of the number of operations performed, the alternative scenarios predict a noise reduction. Figures 14 and 15 also show that the spread of the UAV operations throughout the day do not pose a noticeable advantage regarding noise emission, as the spread versions of each scenario overlap them. This is due to the UAV generating a lower level of noise which is occluded by the aircraft with higher noise emissions. From a noise standpoint, Scenarios 4, 5 and their UAV-spread versions appear to be the ones with lowest emissions.

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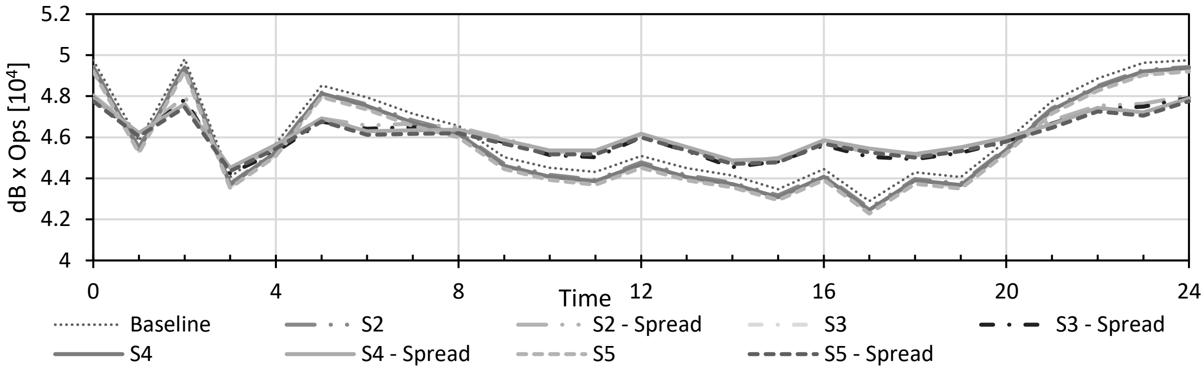

Figure 12: Noise x operations generated during takeoff throughout a day of nine different scenarios. The noise of each individual operation is algebraically added up.

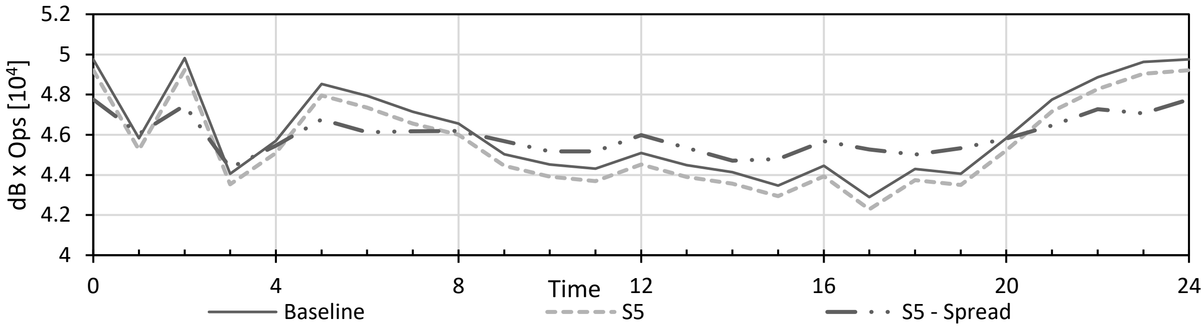

Figure 13: Noise x operations generated during takeoff throughout a day of three different scenarios. The noise of each individual operation is algebraically added up.

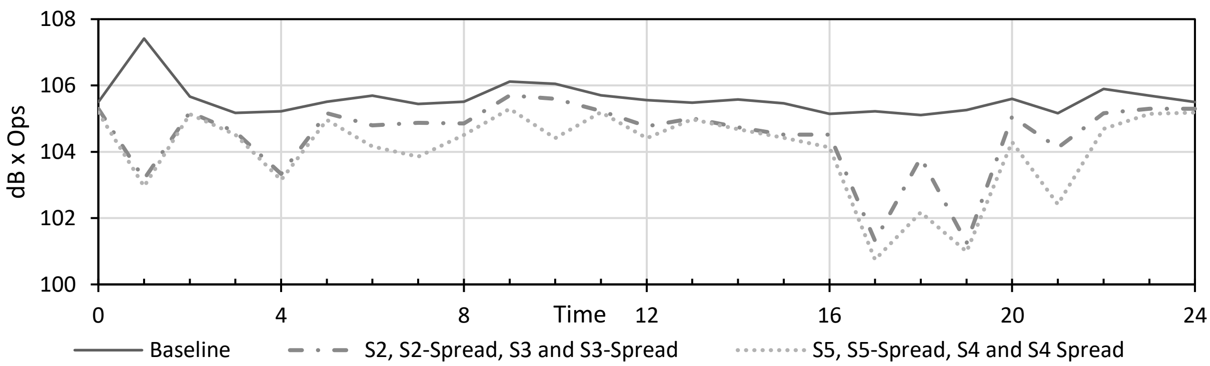

Figure 14: Noise generated during takeoff throughout a day of nine different scenarios. The noise of each individual operation is logarithmically added up.

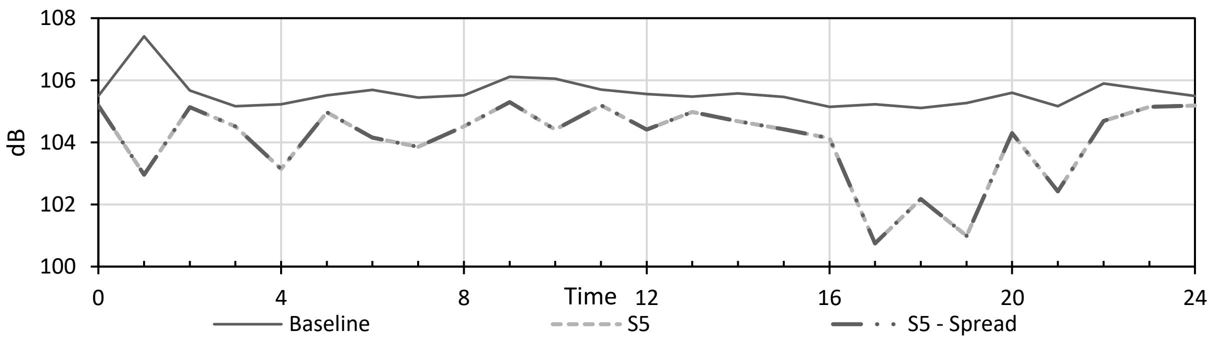

Figure 15: Noise generated during takeoff throughout a day of three different scenarios. The noise of each individual operation is logarithmically added up.

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4. Conclusions

This research is founded on the premise that current aircraft performing short and medium-range cargo transportation can be substituted by UAV. This premise is likely to be true given the current research and developments being performed by several companies. An additional assumption is the fact that such a replacement would entail an increase of the load factor of the aircraft. This increase comes from the possibility that UAV tend to have lower load capacity and are more suitable to an on-demand use. This advantage makes it possible that, even when the number of aircraft in a UAV scenario is greater, lower emissions are generated.

Results show that, at the current growth rate, pollutant emissions can become a much harsher problem in the future than nowadays. New technologies, such as the replacement of currently manned aircraft by UAV may be a useful alternative to avoid such a steep growth. However, this is not enough to produce a substantial reduction of emissions, and further development of several technologies, such as batteries, is necessary to tackle the problem. Should other factors favoring lower emissions improve in future years (such as decreasing cargo traffic), the effect of switching from manned aircraft to UAV would still be positive. Additionally, as stated before, this effect would be even stronger if improvements in technologies related to propulsion systems further lower emissions.

Regarding noise emissions, it is clear that using smaller airplanes is advantageous; more so when fuel-engines are replaced by electrical ones. However, this potential advantage does seem to be softened by the need to increase the number of operations when switching to small UAV. Decreasing even more the size of UAV could further reduce the noise generated by each aircraft and therefore that of the aggregate too, as noise increases slowly with the number of noise sources. In addition, the switch to UAV allows for an easier redistribution of the takeoff and landing operations at different times of the day, which can be used to diminish the noise and peaks in saturation at airports. In addition, the use of UAV has strong implications in air traffic management and could increase traffic capacity.

Using UAV in cargo transportation may prove very advantageous to reduce the emissions of polluting and greenhouse gases. All in all, using UAV as a replacement for current aircraft in cargo transportation poses a positive outcome which needs to be backed up by further technological development in other areas.

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