

Article

Strategies to Reduce Pollutant Emissions in the Areas Surrounding Airports: Policy and Practice Implications

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Abstract: Airport areas generate significant air pollution from both air and surface traffic. Policy makers often address this by considering single contributions, either from rubber-tired vehicles or aircraft, leading to an underestimation of the non-considered-mode's impact. Similarly, literature on airport pollution often focuses on specific case studies, evaluating either surface or air traffic. Understanding the overlap of these contributions requires calculation of emissions from both traffic modes. This raises two research questions: which is the major contributor, and what mitigation measures can be applied? This paper addresses these questions through two Italian case studies. In the first, we estimated emissions from passenger cars, buses, and aircraft in a medium-sized airport representative of similar facilities across Italy and Europe, calculating emissions using COPERT for surface modes and ICAO methodologies for each LTO cycle. Results showed that aircraft emissions were significantly higher than those from surface vehicles. To address this, the second case study examined four mitigation measures at take-off and landing at another Italian airport, recalculating emissions via the same methodologies. The paper details the methodology process, presents results, and discusses the management of air-operations' effects at urban airports within local mobility policies and practice, all within the research goal of advancing knowledge farther afield.

Keywords: emissions; aviation; airports; traffic; sustainability



Citation: Corazza, M.V.; Di Mascio, P. Strategies to Reduce Pollutant Emissions in the Areas Surrounding Airports: Policy and Practice Implications. *Future Transp.* **2024**, *4*, 820–833. <https://doi.org/10.3390/futuretransp4030039>

Academic Editor: Lynnette Dray

Received: 11 June 2024

Revised: 7 July 2024

Accepted: 22 July 2024

Published: 1 August 2024



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1. Introduction

Historically, aircraft were viewed as the most environmentally detrimental travel option, perpetuating the perception that aviation represented an ecologically unchecked sector compared to surface transport. But before the COVID-19 pandemic, aviation contributed approximately 2% of global greenhouse gas emissions across various economic sectors [1,2], with projections at that time indicating a potential 10% to 15% increase in air traffic by 2050 [3,4]. Yet, although air transportation is a pivotal driver of economic development, generated emissions are still a problem. This manifests at different levels, from cruise altitudes (26,000–39,000 ft) where they contribute to global air pollution and climate change [4,5], to ground level during the landing and take-off (LTO) cycle, directly at the airport, where they adversely impact nearby air quality [6,7], and represent an additional source of air pollution to those associated with “ground” activities and local land use, in the areas where airports are located. This explains why, although extensive research has delved into emissions per flight hour [8,9], with studies emphasizing the potential repercussions of LTO operations on air quality and noise levels [10,11], further investigations are imperative to optimize operations at ground level, throughout the complete LTO cycle [12].

Aircraft engine operations emit pollutants like hydrocarbons (HCs), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM) [13]. But emissions do not originate only from aircraft engine exhausts. They are also generated from ground facilities and operations (refueling, maintenance, heating), and from the airport itself, serving as an attractor/generator of rubber-tired traffic

around its premises [14,15]. The grey and scientific literature on ground-level emissions is extensive [16–18], in part because a multitude of factors need to be considered, including detailed flight information, climb and approach modes [19], aircraft fleets' performance, payload [20], runway availability [21], specific inventories [22,23], and airport large-scale benchmarks [24–26]. Moreover, emissions exhibit variations across operational phases [27]. At ground level, prolonged and low-thrust taxiing phases (taxi-in and taxi-out) result in inefficient combustion (typically indicated by hydrocarbon generation) and other higher emissions, which further exacerbates environmental concerns. In this, operating time during aircraft taxiing is one more element to consider. Between 2006 and 2007, taxiing time exceeding 40 min increased by 20% in the USA. In Europe, taxiing time ranging from 10% to 30% of total flight time resulted in fuel consumption of approximately 5–10% of the total burned during the entire flight cycle [28]. The surge in air traffic demand leads to a higher rate of growth in taxiing than cruising time, primarily due to increased on-ground congestion and controller overload [29–31]. Numerous studies have explored emissions from aircraft in various taxiing modes, including single-engine taxiing [28], dispatch towing [28,30], onboard systems [30], and optimization of surface traffic management [32]. Many of these assessments have established inventories under standard operating conditions [33], neglecting the influence of real environmental conditions, such as air temperature and pressure.

Addressing the challenges associated with emissions from LTO operations is a multi-faceted issue that requires a multi-pronged approach. As well as the assessments of the operations mentioned, from a technical perspective, it involves advancements in aviation systems, including the strategic roles of sustainable fuels in the future [34–36]; efforts to optimize routes, leading to substantial reductions in carbon dioxide emissions [9,37]; and eventually, progress in electrification, following trends observed in other sectors like transit [38,39].

There are other problems associated with pollution in airport areas, particularly those affecting the inhabitants living nearby, leading to noise and public-health issues. The literature on noise pollution is vast, mostly focusing on impacts [40,41], modeling methodologies [42,43], and mitigation actions [44,45], with many case studies where the community perspective is central [46]. Sources in the field of public health are also abundant and extensively described elsewhere [15]. Additionally, some sources address other topics, typically the economic aspects of the problem [47,48], the contribution from sources other than engine exhausts [49], the scale of the effects [50], and the mortality rates [51], although it is generally acknowledged that more information is needed and that a comprehensive community perspective is essential to find shared solutions.

On the policy front, the implications of operating in an environmentally friendly manner are extensive and remain a topic of ongoing debate [52,53], in part because of the complexity of the policy process [54], with local communities often being vocal about problems associated with living close to an airport environment and calling for specific participatory processes [55,56]. However, when assessing environmental conditions of urban areas where airports are located, policymakers often focus on air pollution generated by either rubber-tired vehicles or aircraft, often neglecting the combined impact of both. To gain a comprehensive understanding, it is crucial to calculate emissions from both sets of modes, recognizing the influence of each, if the goal is to assess the overall impact on airport environments and communities. In a given airport area, this raises two research questions: (i) identifying the major contributor between surface traffic and air traffic, by determining the magnitude of each in generating emissions, and (ii) exploring mitigation measures for the primary contributor.

The paper addresses these questions through two Italian case studies. The first, involving a medium-sized one-runway airport, indicated that aircraft emissions significantly outweighed those from surface vehicles. This result introduced the second case study (again a one-runway airport) which examined four mitigation measures for ground emissions during LTO cycles, calculating emissions with the same methodology adopted in the

first case, and assessing their potential to decrease pollution, so as to reduce the impact of ground operations on airport environments. This paper, therefore, describes the adopted methodology (Section 2); elaborates on the results in response to the two research questions mentioned above (Section 3); and discusses the findings in terms of potentially more sustainable operations and policies for both surface and air transport, and land use, all with the overarching research goal of contributing to advancing knowledge in this area. In particular, (as explained in Section 4.1), by answering the two research questions, the study aimed to fill a gap in land-use and mobility policies with regard to emissions in the airport environment, where pollution from air traffic is often neglected in urban master plans or mobility plans, and vice versa, pollution from surface transport is little considered in airport master plans.

2. Two Cases, One Methodology

The two twinning case studies mentioned above called of a univocal methodology, to ensure consistency of results (Figure 1). The first step, common to both areas, was to proceed with the emission simulation by employing well-known modeling methodologies, specifically the International Civil Aviation Organization (ICAO), and COPERT for air traffic and surface traffic, respectively (both detailed in [57,58]). Moreover, compliance with the European Environmental Agency (EEA) regulations [59] ensured consistency in both modelling processes. This methodological step was affected by the observation that even the ultimate supranational climate agreements (e.g., COP26, Glasgow, 2021) do not establish specific regulations for the greenhouse gas emissions generated by the transport sector, which compelled us to rely on consolidated methodologies [60].

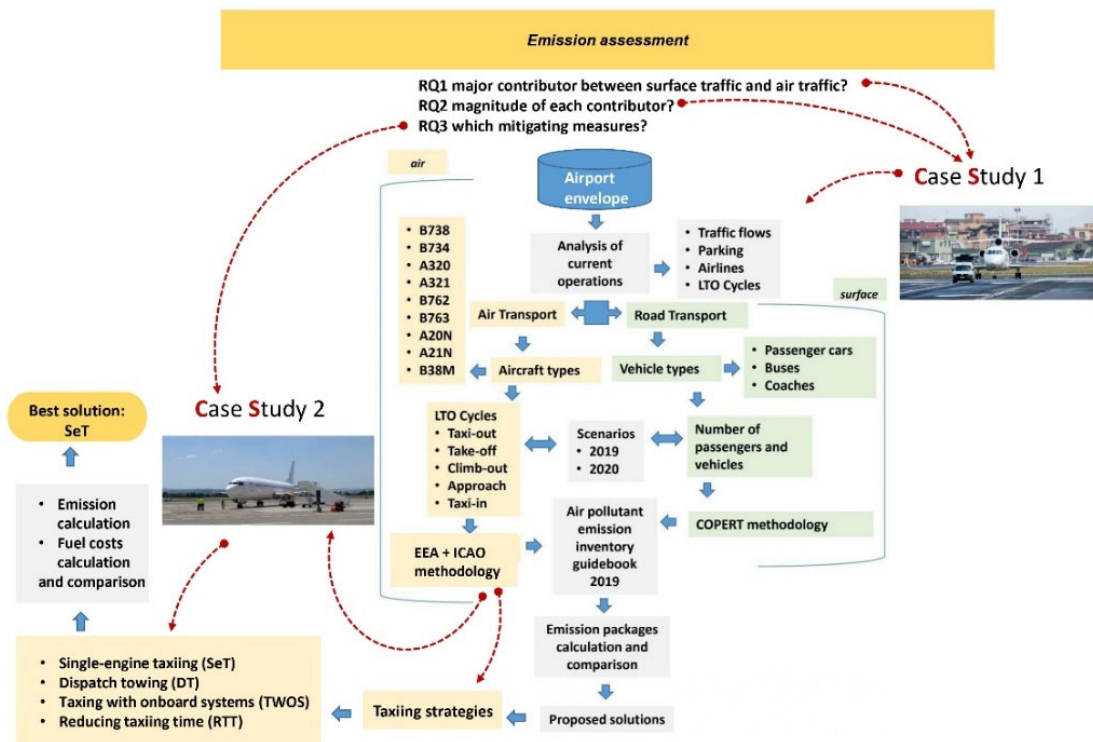


Figure 1. The adopted methodology.

For data collection, in the first case study, traffic surveys for cars included vehicle counts, and the make, model and plates (to associate each vehicle with a EURO-compliance engine standard) and actual occupancy of each car. The same type of analysis was carried out for aircraft (for both case studies), via data provided by two of the most common live flight trackers available on the web, and considering additional parameters like the

amount of fuel burnt per single LTO cycle (in kg) and the standard seat capacity for typical accommodation configuration.

One more issue to consider was the development of LTO operations associated with emission generation. Here, the LTO cycle itself is an important parameter as it encompasses distinct stages, including approach, landing, taxi-in, taxi-out, take-off, and climb-out, with the duration of each phase regulated by ICAO standards [61]. Within LTOs, duration assumes significance as it delineates the period during which an engine operates in a specific scenario. Consequently, it influences the thrust requirements of individual engines, the corresponding fuel consumption, and the types and quantities of pollutants emitted. For instance, during take-off, carbon dioxide may be predominant [62], yet ultrafine particles should not be overlooked, as studies indicate their detectable impact up to 10 km from the airport premises [63]. Essentially, each LTO stage not only varies in duration but also in the specific thrust demands placed on an aircraft's engines. As an illustration, typical engine power settings include idle (taxi-in) at 7%, take-off at 100%, climb-out at 85%, and approach (approach and landing) at 30% [61,64].

The final factor considered was the environment where the emissions were calculated, which included both airside and landside areas in the first case study. These areas were treated as a unified space or "airport envelope," a kind of cylindrical volume with height corresponding to the LTO cycle's 3000 ft altitude and base represented by a 2.5 km radius surface catchment area. For the case in hand, the catchment area included, along with the airport's airside and landside, two major arterials connecting the airport to the city generating heavy traffic volumes, especially in peak-time hours. Collected data on both air and surface traffic (the latter by the traffic counts mentioned above) "fed" the fuel-emission models, evaluating their magnitude and impacts on the airport envelope's volume.

Once we had determined the major pollutant between air and surface modes and the magnitude of the emissions generated, for the second question, the analysis moved to the second case study. Here, a large literature review on potential mitigation measures strictly associated with LTO phases (further elaborated), showed that avenues to explore for taxiing phases implied strategies such as reducing operating engines, resorting to electrification, or minimizing taxiing duration. The scientific literature developing comparative analyses is still in progress [65,66], whereas the lion's share of the literature is associated with studies on design improvements for engine parts [67,68].

To this end, to simulate the potential reduction in pollution associated with taxiing phases we built scenarios where the emissions generated by each of these taxiing strategies were simulated via the same models as those used in the first case study. This enabled a cross comparison, with the cost of fuel associated with each strategy highlighting the best solution and its potential in saving resources.

As described in the introductory section, the methodology relied on two case studies, representing typical middle-sized airports in Italy. Both were close to densely inhabited urban areas, and representative of the emission generation due to local air and surface traffic, with comparable weather effects in terms of temperature-inversion and low-wind-speed phenomena. The impact of the airport on air pollution was addressed by considering different aspects of local mobility: those due to access mobility (road vehicles) to the airport and those due to the mobility of aircraft. Unlike the majority of examples available in the literature, which are based on single case studies, having two case studies enabled us to study emission patterns in each "envelope" and develop solutions for the scenario-building phase according to consolidated facts. The final selection of mitigation measures, described in Section 3.2, was therefore not "site specific" but applicable to any airport with similar operational features to those observed in the two case studies. Likewise, the overall approach can be applied to any airport where access is limited to road mobility (with no rail supply), and results applied to medium-sized airports, although the methodology can be up/downscaled to any type of facility.

This study can be used as a reference for the management of land adjacent to airports, for the planning of both infrastructure associated with access to the airport and that dedicated to the ground mobility of aircraft (taxiways).

3. Results

The methodology described above was designed to provide scientifically sound responses to the two research questions, i.e., (i) assessment of the magnitude of emissions generated by surface traffic and air traffic, to identify the most pollutant mode, and consequently, (ii) the development of emission-mitigation measures. Although it might be intuitive that air traffic contribution can be disproportionate if compared to that generated by rubber-tired traffic, the magnitude of both is seldom compared in the literature, but this comparison is needed in order to understand the potential of the proposed measures, especially in terms of operational feasibility and efficiency.

3.1. Magnitude of Emissions Generated by Aircraft and Rubber-Tired Vehicles in the Case of the First Medium-Sized Airport

As previously stated, in addressing the initial research inquiry concerning the primary emitter of pollutants, a simulation was developed to analyze daily air and surface traffic and their respective emissions at a medium-sized airport in central Italy. Before the onset of the pandemic, this facility experienced approximately 53,000 air movements annually, accommodating over 5.5 million passengers. Commuting to the airport was predominantly facilitated by chartered buses and coaches (53.5%), private cars (26.5%), and taxis and rentals (20%). Traffic surveys verified these percentages, which were linked to various average occupancy rates, such as 1.25, 1.5, 2, and 3 for passenger cars, according to the literature [69], to assess the yearly demand accessing the premises. Likewise, surveys confirmed the buses' and coaches' full occupancy, which was not surprising as these represent the fastest and least expensive connection from the city to the airport serves.

The outcomes of the simulation, presented in Table 1 and using the 1.25 occupancy rate as an example, address the first research question, demonstrating that the contribution of surface traffic emissions was essentially minor when compared to those of the aircraft. Emissions generated by rubber-tired traffic were still negligible in the scenarios with cars associated with the lower occupancy rate, although the traffic survey showed that 1.25 was the actual average rate. These findings underscore the need for urgent exploration of more environmentally friendly solutions to oversee air-traffic ground operations.

Table 1. Yearly emissions comparison.

Mode	Traffic	Pollutant Emitted, Mass (kg)			
		CO	CO ₂	HC	NO _x
Car ¹	2,102,508 (vehicles)	1766	299,931	71	794
Aircraft	26,128 LTO cycles	129,778	64,278,872	13,053	314,200

¹ 1.25 occupancy.

Table 1 highlights the significantly different contributions to air pollution of road vehicles and aircraft. Air traffic produced 73 times the CO emissions compared to road traffic, 214 times the CO₂, 184 times the HC, and 396 times the NO_x. It should be noted that although emission diffusion was not investigated, local low-wind-speed and occasional temperature-inversion phenomena allow pollutants to accumulate near the ground, thus exacerbating the magnitude of the pollution levels.

However, Table 1 answers the first research question by clearly showing that aircraft were the primary source of emissions within the airport envelope. This leads to the second research question, i.e., to discern potential mitigation measures to operate on the predominant contributor; namely, to diminish environmental impacts during the critical phases of LTO operations.

3.2. Identifying Mitigating Measures to Improve Ground Operations and Their Achievable Benefits

To answer the second research question, four different taxiing solutions were studied, taking as a case study one more Italian airport, operating at a slightly larger scale than the one previously considered (in this case 70,000 movements/year and around 9 million passengers, in the pre-pandemic period).

More specifically, the considered measures were:

- (a) SeT—Single-engine taxiing, with aircraft operating half the engine at ground level, which corresponds to an emission reduction equal to the amount of pollutants generated by the turned-off engine when operational.
- (b) DT—Dispatch towing, with aircraft towed from gate to runway, without operating engines and power provided by an auxiliary power unit (APU). However, since both APU and the towing vehicle generate emissions, these can be computed according to three options, i.e., traction fueled by petrol (DTp), diesel (DTd), or electrification (DTe).
- (c) TWOS—Taxiing with onboard systems, by exploiting electrification of landing gears for parallel traction, which provides aircraft with autonomous maneuvers with the main engines off, with the exception of heating/cooling requirements, and APU operating at maximum power [70];
- (d) RTT—Reducing taxiing time, thanks to the optimization of ground-handling procedures and the re-design of aprons and taxiway layouts. This can be simulated by building several sub scenarios, according to the expected reduced taxiing times by 1, 2, and 3 min (thus building RTT1, RTT2, and RTT3 sub scenarios, respectively), to be compared to baseline operations. The emissions in the reference scenario were evaluated considering the taxiing times recorded at the airport. Possible reductions in taxiing times were evaluated with a simulation of aircraft movements consistent with the airport actual operations.

The ICAO methodology [12] adopted for the first case study (described in [58]) was replicated for the calculation of fuel consumption and emissions, which are reported in Tables 2 and 3, respectively.

Table 2. Fuel consumption scenario comparison.

Taxiing Measures at LTO Phases	Fuel Consumption	
	(ton)	(%)
Reference	21,448	
SeT	19,603	−8.6
RTT1	20,617	−3.9
RTT2	19,787	−7.7
RTT3	18,956	−11.6
DTd	19,161	−10.7
DTp	19,161	−10.7
DTe	19,161	−10.7

For a given LTO cycle, all taxiing options contributed to a noticeable decrease in emissions. However, specific phases of taxiing required additional attention. For example, during taxi-in, employing SeT resulted in a 10.1% decrease, while implementing more efficient surface traffic management resulted in reductions of 16.0%, 31.9%, and 47.9% for RTT1, RTT2, and RTT3, respectively. These measures had a similar impact on all pollutants due to reduced engine taxiing time. However, using traditional towing methods with internal combustion vehicles, whether diesel or petrol-powered, increased pollutant levels due to emissions from the towing vehicle and APU. Diesel towing raised NO_x by 109% and PM by 240%, while petrol towing increased CO by 344%. Electric towing vehicles presented a more favorable option, with only a 25% increase in HC emissions. TWOS resulted in reductions in pollutants, although there was an 18.3% increase in NO_x and a minimal 1.2% rise in fuel consumption. During the taxi-out phase, which typically lasts

longer than taxi-in, containing emissions is more effective when the aircraft’s main engines remain off, leading to significant fuel savings. Under SeT conditions, there was a notable 30.2% reduction in emissions, while improved ground operations led to reductions of 7.9%, 15.8%, and 23.8% for RTT1, RTT2, and RTT3, respectively. Onboard systems reduced fuel consumption by 39.0%, along with a 57.6% decrease in HCs and a 60.4% drop in PM. Electric-powered towing systems offered substantial fuel savings at 41.3%, although this advantage was offset by increased taxiing time. Towing with internal combustion vehicles, whether diesel or petrol, during taxi-out, led to emissions exceeding mitigation objectives, with diesel towing causing a 199.8% increase in PM and a 73.4% increase in NO_x, and petrol towing resulting in a 308.6% increase in CO.

Table 3. Emission generation scenario comparison.

Taxiing Measures at LTO Phases	Pollutants Emitted (ton)											
	HC		CO		NO _x		SO _x		PM		CO ₂	
	(ton)	(%)	(ton)	(%)	(ton)	(%)	(ton)	(%)	(ton)	(%)	(ton)	(%)
Reference	19		193.1		267		21.4		2.6		67,668	
SeT	15	−21.1	151.3	−21.6	259	−3.0	19.6	−8.4	2.4	−7.7	61,489	−9.1
RTT1	17.2	−9.5	174.3	−9.7	263.4	−1.3	20.6	−3.7	2.5	−3.8	65,047	−3.9
RTT2	15.4	−18.9	155.4	−19.5	259.8	−2.7	19.8	−7.5	2.4	−7.7	62,427	−7.7
RTT3	13.6	−28.4	136.6	−29.3	256.2	−4.0	19	−11.2	2.3	−11.5	59,806	−11.6
DTd	23.9	25.8	166.6	−13.7	295.8	10.8	19.2	−10.3	4.1	57.7	62,499	−7.6
DTp	30	57.9	762	294.6	269	0.7	19.8	−7.5	2.3	−11.5	62,470	−7.7
DTe	19.9	4.7	153.2	−20.7	258.8	−3.1	18.6	−13.1	2.2	−15.4	60,453	−10.7
TWOS	11.4	−40.0	117.6	−39.1	264.1	−1.1	19.4	−9.3	2.2	−15.4	61,313	−9.4

Cost-Saving Potential

The cost analysis shows additional potential for the four measures. In this case the key parameter, i.e., the total fuel cost (T_c) for each measure, is calculated by:

$$T_c = F_c \cdot U_f \tag{1}$$

where F_c represents the fuel consumption associated with each considered solution, and U_f is the unit fuel price as sourced from [71,72].

Table 4, where T_c for each measure is compared with the baseline scenario, highlights that the most significant cost reductions were achieved when solutions implied electrification (i.e., DTs and TWOS), with both electric-vehicle towing and onboard systems offering comparable savings. Conversely, petrol is a no-option as it resulted in higher overall costs compared with the reference scenario. A significant cost reduction could also be achieved by decreasing the taxiing time; however, the reduction was relevant when greater than 3 min (solutions RTT2 and RTT3).

Table 4. Yearly fuel costs.

Taxiing Solution	Kerosene (Euro)	Diesel/Petrol (Euro)	Total	Difference with the Reference Scenario (Euro)	Difference with the Reference Scenario (%)
Reference	11,825,396	0	11,825,396		
SeT	10,808,411	0	10,808,411	−1,016,985	−8.60
RTT1	11,367,408	0	11,367,408	−457,988	−3.87
RTT2	10,909,420	0	10,909,420	−915,976	−7.75
RTT3	10,451,432	0	10,451,432	−1,373,963	−11.62
DTd	10,564,583	1,236,851	11,801,434	−23,961	−0.20
DTp	10,564,583	1,460,274	12,024,857	199,461	1.69
DTe	10,564,583	0	10,564,583	−1,260,813	−10.66
TWOS	10,714,738	0	10,714,738	−1,110,658	−9.39

4. Discussion of Policy and Management Implications

The two case studies demonstrate that the goal of reducing emissions generated by transport must be addressed globally by analyzing all modes of transport and their connections. Airports perfectly showcase how multimodality impacts air pollution, as passengers arrive by car, bus, or train, and depart by plane, and vice versa. This is why, when dealing with airport areas, air pollution must be considered as the contribution of both surface and air modes, although the magnitude of the latter is much greater, as shown in the previous sections.

The results, therefore, suggest two lines of action to mitigate emissions:

- (i) Adaption of land-use and mobility regulations and policies to include air transport when planning and enforcing measures involving multimodality;
- (ii) Management of airport operations by adopting more sustainable solutions, like those tested in the second case study.

Each of these actions complements the other and they must be pursued in synergy, as detailed in the following sections.

4.1. Acting on Land-Use and Mobility Policies and Regulations

The first line of action considers that, although environmental drivers might be the same, airports' master plans, local surface mobility, and land-use plans have, thus far, mostly been developed independently. This also explains why emissions due to air traffic are often not considered in urban master plans or mobility plans, and vice versa. The reasons are many: (i) different time horizons among plans (land-use and airport master plans are usually more "farsighted" than mobility plans, which are short-to-medium term); (ii) different actors (mostly local entities in mobility and land-use plans versus a mix of national and supranational bodies involved in airport master plans); (iii) different availability of resources (traffic and sustainable-mobility plans are often "low cost," relying mostly on the enforcement of regulatory measures); and (iv) the consideration of airports' functions as similar to any other surface transport facilities, although different since the dominant field of operations is not surface.

However, airports, due to their functions and land occupancy, can be considered actual urban centers [73], with pollution being generated at ground level, within the "envelope", and affecting the surrounding areas. This means that comprehensive policies must be developed, with the ground measures mentioned above meeting the requirements of both surface regulatory tools (local mobility and land-use plans) and airport master plans. For the former, these can be included among the surface strategies to mitigate the effects of aircraft pollution and, for the latter, they can be forecast as structural to support the sustainable development of operations.

Engaging with airlines, airport operators, ground-handling companies, and local communities becomes imperative. Although this might appear feasible within the development of airport master plans, communities are often considered a limiting factor for airport capacity and operability [55,74], and thus not central in the process. In turn, the multiplicity of actors involved in airport operations, as noted in Section 2, and their "non-local" status often seem to exclude them from typical participatory processes in mobility plans, with few cases reported in the literature, and these mostly focused on noise problems or privatization issues [74,75]. This means that participatory processes need to be revised (also in the light of the successful case studies in the literature [51–53]), with airport stakeholders and local communities being equally active in supporting the adoption, development, and implementation of effective strategies for reducing emissions, as they both share a common environment. Needless to say, this also implies transparent communication and collaboration among the parties to address concerns and share benefits. As a result, such enlarged participation would foster collaboration between aviation authorities, local governments, and transportation agencies to ensure the seamless implementation of emission-mitigation measures. Moreover, it would develop more integrated mobility plans that consider both aircraft ground movements and surface transportation within and around the airport.

In developing more comprehensive policies, it is important to note the potential provided by the four types of ground measures to better meet noise-mitigation requirements. Each of the tested ground solutions can contribute to airport sustainability, not only by reducing emissions and fuel consumption but also by leading to less noise pollution, aligning with noise abatement policies. SeT would result in lower noise levels compared to dual-engine taxiing, TWOS since electric motors are quieter than jet engines, RTTs due to reduced taxiing times, and DTs would eliminate aircraft engine noise during taxiing. Although noise abatement is central in airport master plans, it is often considered secondary in many urban mobility plans due to the major emphasis usually placed on air-quality requirements. However, the tested ground solutions can be beneficial in mitigating the overall noise levels in the airport surrounding areas.

The implementation of these ground measures might require additional land occupancy for potential operational efficiency improvements. For example, RTT with the redesign of aprons and taxiways layouts might imply more buffer zones; the same applies for TWOS, with specific areas for parking and maintaining the electric tugs, electrified landing gear systems, and charging infrastructure. This might become a problem for small-sized urban airports close to densely inhabited areas, where land availability can be limited. This represents a caveat to consider in the development of land-use policies, regardless of the mode (air or surface) affected.

4.2. Managing Operations via More Sustainable Solutions

The four ground measures imply a revision of operations. In terms of ground-movement efficiency, SeT would affect taxiway utilization, as ground control might need to manage potentially slower-moving aircraft and plan for increased spacing to accommodate different taxiing speeds. Coordination with ground-handling services might also need improvement to ensure efficient pushback procedures when aircraft operate on one engine. At the same time, a reduction in total pushback time has already been observed for TWOS [76], and it is intuitive that more electrification could lead to general improvements since electrified landing gear systems can provide more precise and efficient ground movement, thus increasing taxiway efficiency. DTs could imply adjustments to taxiway use and scheduling to accommodate tow vehicles, which may have different speed and handling characteristics compared with taxiing aircraft, and also associated with trajectories [77]. Lastly, RTTs would require implementation of optimized taxi routing systems to minimize taxiing distances and times [78], potentially increasing the number of takeoffs and landings per hour. Revising taxiway utilization also leads to redesigning of sequencing and spacing, since, especially for SeT, air traffic controllers must consider adjustments in runway occupancy-time calculations, as single-engine taxiing may alter the time needed for aircraft to vacate runways after landing or before takeoff.

In terms of maintenance, TWOS will require the management of charging infrastructure, including the installation of charging stations or recharging power sources, and the consequent need to upgrade maintenance facilities to handle this new technology, including tools and equipment for electric systems. Similarly, RTT would pave the way for advanced ground control systems, such as Airport Collaborative Decision Making (A-CDM) [79], Surface Movement Guidance and Control Systems (SMGCSs) [80], and more generally advanced models [81], to enhance efficiency. RTTs would also call for adjustments to slot-allocation policies to maximize the benefits of reduced taxiing times, ensuring efficient use of airport capacity, and forecasting a potential for increased airport throughput due to reduced ground-movement times. Infrastructural changes should also be planned, such as additional high-speed taxiways or rapid exit taxiways to facilitate faster ground movements specifically for RTTs, charging opportunities for TWOS, modifications to taxiways and ramps to facilitate safe and efficient towing operations for DTs (along with the need for an appropriate number of tow vehicles to meet the new demand, particularly during peak times), and eventually for SeT, additional turnoff points or wider taxiways.

Significant reductions in fuel consumption, as shown in Table 3, can lead to substantial cost savings for airlines. Likewise, for SeT and RTTs, potential reductions in overall engine maintenance costs can be achieved if the practice leads to more balanced engine use and reduced wear. Results also show that significant cost savings are associated with reduced fuel consumption, with DTs and TWOS offering the most considerable savings. For example, RTTs yield substantial cost reductions: reducing taxiing times by 3 min, if each minute of taxiing consumes approximately 15 kg of fuel [82], saves 45 kg of fuel per flight. For an airport with 200 departures daily, this translates to a daily saving of 9000 kg of fuel. At around EUR 0.8 per kg [83], the daily savings amount to EUR 7200, or roughly EUR 2.6 million annually.

In the case of electrification, a potential reduction in engine maintenance costs is possible, as engines are not used during taxiing. However, while the above calls for a revision of operation coordination and organization (including areas like training, certification, and safety procedures, all with associated costs), it also calls for upfront costs associated with initial investment in technology and infrastructure. The savings mentioned cannot be reduced since they benefit airlines and not airport authorities. This means balancing such investments with the expected environmental benefits (reduced carbon footprints of both facility and operations) and the potential for increased operational efficiency, mostly due to the RTT solutions.

5. Concluding Remarks

The two case studies show that the dominance of aircraft emissions in airport areas, rather than emissions from surface traffic, during the LTO (landing and take-off) cycle significantly impacts local air quality, calling for several areas of intervention. First, the enforcement of comprehensive land-use and mobility (both air and surface) policies is necessary, as the “envelope” where such emissions occur affects not only airports’ land and air sides but also the surrounding communities. This involves a multifaceted approach and common visions in the development and alignment of regulatory tools like airport and urban master plans, and traffic and sustainable-mobility plans, along with strong cooperation between aviation authorities, local governments, transportation agencies, and community stakeholders. Public and stakeholder engagement is a prerequisite in this process, as ensuring transparent communication and collaboration with local communities and stakeholders is vital. This will foster acceptance and support for environmental measures and integrated planning efforts.

Factually, integrating and coordinating policies should focus on the management of taxiing operations, especially when the taxiing phases are prolonged, as these contribute substantially to ground-level emissions. The goal is to achieve significant environmental benefits for the airport’s entire surrounding areas and communities. This is under the general goals of optimizing ground operations, employing advanced technologies, and integrating sustainable fuels.

This study evidenced that mitigation measures based on four different taxiing modes (i.e., single-engine taxiing, dispatch towing, taxiing with on-board systems, and reducing taxiing time) represent sound solutions, in both the short and the long term. More specifically, in the short term, single-engine taxiing appears to be the best solution for both the taxi-in and taxi-out phases of the LTO cycle, as the overall reduction in emissions ranges between 3% and 21%, and fuel consumption is reduced by 8.6%. In the long term, the reduction in taxiing time in the taxi-in phase results in the highest emissions and fuel reduction (−31.9% compared to the current scenario), while in the taxi-out phase, taxiing with on-board systems results in the best solution (with up to −57.6% for hydrocarbons).

These solutions require investments, especially if associated with the introduction of new technologies, typically the potential of electrification of ground operations, which shows considerable promise in reducing emissions and fuel consumption.

This paves the way for future work, i.e., a focus on economic and environmental trade-offs. The economic implications of implementing DT, TWOS, and RTT3 strategies

appear to be substantial. These measures not only offer direct cost savings through reduced fuel consumption and maintenance costs but also enhance operational efficiency, improve aircraft utilization, and align with environmental regulations. The cumulative financial benefits for airlines and airports make these measures highly attractive, fostering a more sustainable and economically viable aviation industry. A detailed analysis of the economic costs and prospective environmental benefits of the strategies based on these mitigation measures will help prioritize investments, balancing the upfront costs of new technologies against long-term savings in fuel and maintenance costs. This will significantly enhance the sustainability of airport operations and reduce the environmental impact of aviation.

Author Contributions: Conceptualization, M.V.C. and P.D.M.; methodology, M.V.C. and P.D.M.; validation, M.V.C. and P.D.M.; formal analysis, P.D.M.; data curation, M.V.C.; writing—original draft preparation, M.V.C. and P.D.M.; writing—review and editing, M.V.C. and P.D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. Restriction may apply due to privacy reasons.

Conflicts of Interest: The authors declare no conflicts of interest.

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