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Airports as Sensitive Areas to Mitigate Air Pollution: Evidence from a Case Study in Rome

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Abstract: The environmental concerns are behind urban and regional mobility plans, with one of the goals being to manage surface traffic to reduce emissions. Yet, in sensitive areas such as those around airports, the contribution to the emissions generated by air traffic are commonly not considered. The research goal of this paper is to quantify and compare the magnitude of the emissions generated by both air and surface traffic, taking the second airport in Rome as an example, in the awareness that a proper knowledge of the emission phenomena might help steer local transport policies towards more appropriate and sustainable solutions. The paper describes the case study's regulatory and land use frameworks both affecting the current traffic patterns around the airport and the emission generation, along with the methodology adopted to quantify the emission magnitude of both air and surface modes; as a result, air traffic emissions are not even comparable in magnitude to those from surface modes. In light of that, implications for surface transport policies are presented, leading to a revision of current mobility plans, and solutions to minimize emissions during land and take-off operations suggested, although problems for their implementations are acknowledged in the conclusions. All within the additional goal to advance the research further afield.

Keywords: air emissions; airports; aviation; car traffic; environment

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1. Introduction

A common feature of transportation and mobility plans at regional or city levels in Europe is the enforcement of measures to mitigate air pollution, and most specifically pollution generated by surface modes. The pursued strategy is also a common trait, hinging on the binomial "incentives to attract passengers to transit and disincentives to the use of private car" [1], with the optimization of the local multimodal supply among its most efficient solutions. This is also the approach adopted by the recently-enforced Mobility, Transportation and Logistics Plan (MTPL) in the Latium region, in central Italy, and the decrease in atmospheric pollution by reducing traffic congestion phenomena is one of its most challenging goals [2]. To this end, the MTPL fosters a balanced development of all transport modes, with a special focus on the surface ones, and specifically addresses some sensitive areas where traffic congestion is particularly severe (and so pollution), among these the two major airports, i.e., Fiumicino (Rome—Fiumicino International Airport "Leonardo da Vinci") and Ciampino (Rome—Ciampino International Airport "G. B. Pastine"). Although it is intuitive that an airport area is a traffic generator, a few facts from the pre-pandemic period well describe in this term the two airports: both serve the city of Rome, a metropolitan area of about 4.3 million inhabitants, with a flow of 19.4 million arriving visitors and 46.5 million stays in 2019 [3]. In the same year, Fiumicino (the main international hub of central Italy and an intercontinental gate to the city) recorded around 43.5 million passengers, whereas Ciampino (the second international airport of the city) around 5.5 million [4]. From these figures, the two airports' strategic role in boosting the local economy and attracting domestic and international visitors to Rome and the region, more in general, is evident.

The MTPL solutions to optimize the regional intermodal supply also include the surface traffic flows generated by both airports, with a series of interventions specifically targeting their accessibility. The specific goal is to improve the quality of the local connections by increasing the transit share, namely via the improvement of the rail supply to Fiumicino and the bus shuttle services to Ciampino over a near horizon. In both cases, it is also planned to develop cycle paths and provide non-motorized options for passengers and staff, similarly to those already available in Vienna and Geneve for instance, and also recommended in the scientific literature [5]. In the far horizon, the MTPL foresees more ambitious interventions such as the extension of the current underground and regional rail networks to reach the airports. The environmental concerns are clearly behind these directions, coherently with the above-mentioned MTPL's goal to decrease the long-lamented congestion problems [6] due to the high local motorization rate and the current infrastructure supply which favors it, as further elaborated.

The MTPL's approach in promoting alternatives to private cars is certainly effective, yet raises a research question, i.e., whether cars are actually the major contributors in generating air pollution around an airport area. If car-vs-aircraft fuel usage and consumption are considered, the following figures show aircraft as relatively fuel-efficient: a 3-occupant car reaches 7570 kg-km per kg of fuel, whereas a long-range wide-body airliner in a maximum payload-range attains 6754 kg-km per kg of fuel, and given that operations might often imply a 75% of attainable payload, smaller figures are usually expected to be achieved [7]. Even considering the hypothetical situation of cars and aircraft equally contributing to air pollution, the research question paves the way for one more consideration, i.e., whether policies and plans such as MTPL show limitations when dealing with air modes or facilities.

The paper responds to all of the above according to the evidence from Ciampino Airport, where the contributions of aircraft and surface traffic in generating pollution have been assessed, with the goal to highlight improvements for the area in line with the sustainability requirements, and eventually deliver a study which may serve as a reference whenever air and surface traffic impacts on an airport environment are to be assessed.

The structure of the paper moves from the literature review on the problem of pollution generated around airport areas and the case study description (Sections 2 and 3, respectively). The methodological approach is then reported (Section 4), with the analysis of the supply and demand patterns at Ciampino airport as initial steps to collect data, firstly in order to "feed" the emission models for both air and surface operations. Results are presented (Section 5), and the road-vs-air emission comparison is elaborated, highlighting differences in magnitude and implications in terms of transport policies (Section 6), with the additional research goal to advance knowledge further afield.

2. The Airport as an Environmentally Sensitive Area

Aircraft were long considered the most polluting travel option by the general public, which led to the common belief of aviation as an unmarked sector by any environmental issue, especially if compared to the greening process of surface transport. This might have been partly true in the past, but nowadays the environmental safeguard is central both in scientific studies and current operations in all aviation fields. The assessment of emissions generated by aircraft at ground level is largely described in the literature from different points of view. Specific assessments due to Landing and Take-Off (LTO) cycles in several case studies are available, stressing the relevance of including specific parameters such as the detailed flight information and the dynamic time in climb and approach modes [8], aircraft fleets performance and payload [9], availability of runways [10], considering specific inventories [11,12], large-scale benchmark [11,13,14], or case-specific assessments. All highlight how LTO operations might affect air quality and increase noise levels, eventually impacting public health [15,16]. When specifically addressing the emission issues, several studies point out how these are not only generated by aircraft engines' exhausts, but also by ground facilities and operations (typically refueling, maintenance, heating), and by the airport per se, as an attractor and/or generator of rubber-tired traffic [17,18].

Environmental concerns are also behind several studies on the potential of new design concepts for aircraft [19,20], typically addressing specific components or processes [21,22], as well as aircraft engines' fuel performance [23–25]. This also implies the revision of current practice, for example, routes optimization, according to which several flight efficiency plans have been issued. One case is represented by the Italian *Free Route* procedure which enables aircraft flying at 9000 m over Italian airspace to navigate along a direct route instead of relying on the fixed route network. This is coherent with the Single European Sky mandate, compulsory since January 2022, and already adopted, besides Italy, by other major European air navigation service providers. Specifically, *Free Route*, thus far, enabled an average saving of 25 km per flight, corresponding to a reduction of 300 kg of carbon dioxide emissions [26].

Policy implications are many, challenging and largely debated (the literature is very vast, and, within it, [27–29] provide interesting considerations); likewise, the introduction of electrification which, as for other sectors and namely public transport, paves the way for new technological and operational horizons [30–33].

On the landside, the commitment to operate "green" is not minor. Many airports worldwide participate in the supranational Airport Carbon Accreditation (ACA) program, coordinated by the Airports Council International, coherently with the United Nations' Sustainable Development Goal 13—Climate Action. ACA rates airports' efforts to reduce carbon emissions, according to six certification levels (Mapping, Reduction, Optimization, Neutrality, Transformation and Transition). Reductions can be achieved through a series of actions, from introducing eco-efficient lighting to using sustainable energy sources so as to become increasingly energy-independent, to optimizing operations via an Airport Collaborative Decision-Making support enabling to share real-time updates on operations among airport and airlines operators, ground handlers, air traffic controllers, etc. Two ACA measures are specifically dedicated to transport: i) the eco-conversion of the ground fleets operating airside into electric, hybrid or gas-powered ones; and ii) the cooperation with taxi companies to lower the vehicles' CO_2 emissions at airport sites [34,35]. Ciampino, together with the other Rome airport Fiumicino, was the first in Europe to achieve ACA 4+ (Transition) by deploying a vast range of measures (from converting the fleet into electromobility to introducing photovoltaic plants, etc.) [36].

Both airside and landside actions are driven by higher level commitments, such as, for example, the supranational "Destination 2050", according to which aviation's major stakeholders and decision-makers in Europe focus on four key areas (aircraft and engine technology; air traffic management and aircraft operations; sustainable aviation fuels; and smart economic measures), to develop a common pathway to net zero CO_2 emissions [37]. Such a common vision would not have been possible without other supranational pioneering programs such as ACARE 2020 and Flightpath2050 in Europe [38] or NextGen in North America [39,40].

A Weak Link

Environmental consciousness is, thus, clearly driving both the aviation and the surface transportation sectors. However, when assessing the environmental impacts these two fields (apparently) do not interrelate and a reason for that might be sought in the separation of the typical regulatory tools enforced in each sector. At the general level, airport areas are usually regulated by two types of tools: master plans and urban transport plans. The former are documents defining long-term land use layouts and regulations to enable an appropriate development of a given area (where the airport is located) or facility (the airport itself); the latter are usually medium or short-term sets of requirements to operate and manage the transport supply (surface services, facilities, modes), and possibly orient demand so as to provide suitable mobility options for people and goods. Both originated from underpinning visions which, as said, have become more and more environmentally conscious. More specifically, master plans (and namely airport ones) are targeted to optimize operations and meet environmental requirements to cope with binding tools such as the Environmental Impact Assessment—EIA or Strategic Environmental Assessment—SEA. Similarly, urban mobility plans are targeted to rebalance the modal share in favor of transit at a local level, and so the large-scale development of Sustainable Urban Mobility Plans—SUMPs, all committed to the typical SEA development of an overall environmentally sustainable vision [41].

Yet, the contemporary trend, according to which larger airports are converting from transportation nodes into actual urban centers, calls for a compromise or an alignment between airport masterplans and urban planning [42], which is lagging behind. At the same time, urban mobility or transport plans are strictly "local" and have little effect over supra-local mobility options, such as air transport, because of the "non-urban" nature of the players (airlines, integrators, etc.).

As a result, on the one hand, airport areas are developed, managed and monitored according to parameters developed within their masterplans and focused on the extent of aviation operations, with specifically-designed models and simulations. On the other hand, surface traffic generated and attracted by airports is managed and monitored according to parameters to assess general traffic flows, again with specifically-designed models and simulations. Emissions are thus evaluated separately: either as generated by air traffic or by surface traffic, and the superimposed effect of both is hardly considered, leading to a misperception of the problem.

Moreover, if the Landing-Take-Off-LTO cycle is considered, operations take place within a 3000-ft altitude (around 900 m), thus within an environment which can be regarded as virtually the same as the surface traffic.

Airport areas can be considered, therefore, a weak link in the assessment of the sustainability of local mobility patterns, for the following reasons:

- Their actual *status of "urban centers" and their "surface" operational environments* (the 3000-ft LTO cycle effect zones) *is still poorly acknowledged*;
- This creates an *underestimation of the air traffic impacts on the air quality in the surrounding areas*, being these rarely included in the surface mobility plans;
- The *integration of surface and regulatory tools and monitoring processes* (as above described) *have different time horizons and involve different actors* the "surface side" is often unable to deal with.

Although the environmental drivers might be common, airport areas, local surface mobility and land use plans develop and progress mostly independently and Ciampino airport is a case in point, as further elaborated. By responding to the original research question originated by such a discrepancy, i.e., which type of traffic is the major contributor in generating air pollution around the airport, it is also possible to introduce additional implications for future integrated land use and transport policies, based on common ground, i.e., the knowledge of the synergetic environmental impacts of the two transport systems.

3. Ciampino Airport as an Urban Node

Ciampino municipality is strongly interrelated with the airport dynamics and vice-versa, with each developing without considering the other's potential. As a result, air operations increased until becoming environmentally unsustainable for the local community, while in turn, the built environment stopped its growth only when abutting the airport area. As further explained, poor land governance, high density, inconsistent regulatory tools, and underestimation of both surface and air traffic progressively contributed to generating the status quo and the current air pollution phenomena.

3.1. The Development of Ciampino Airport

Until the early 1960s Ciampino was the only Rome airport. Originally a military base (opened in 1916), it soon became the third airport in Europe, with total traffic reaching up to 15,000 yearly movements [43]. Due to its location (no strong winds, proximity to a major city arterial and a local railway line), Ciampino also operated as a building yard for airships. Even though the airport underwent a modernization process with the redesign of the runway in 1950, the opening of the new and larger Fiumicino airport eleven years after obviously affected local air traffic and soon Ciampino lost a large share of commercial operations, although not its full civil and military aviation functions. The decline lasted until 2001 when low-cost companies revamped Ciampino, which progressively increased the yearly traffic, with average values of around 50,000 movements and 4.350 million passengers yearly, between 2001 and 2019 [44]. Table 1 describes the volume of traffic comparing the pre-pandemic (2017 and 2019) and 2021 situations.

Currently, the airport has two terminals (one for commercial aviation and another for general aviation) with around 90 bays, hangars and landside support facilities [45].

Table 1. Data on operations at Ciampino Airport [45–47].

	2021	**2019**	**2017**
Movements (unit)	37,219	52,253	54,236
Passengers (unit)	1,621,159	5,879,496	5,885,812
Cargo (tons)	19,324	18,408	17,013
Carriers (unit)	2	2	2
Destinations (units)	34	57	56

The limited number of airlines operating in Ciampino is coherent with its nowadays role of "Secondary Airport", complementing Fiumicino, with point-to-point flights operated by narrow-body aircraft, to serve a demand virtually all European (with just 3% domestic and 3% non-European [46,47]). Continuous investments to renovate airside (taxiways and aprons) and landside facilities (both the passenger and the general aviation terminals) are planned, with recent specific interventions during the 2017–2021 period.

The pre-pandemic air traffic increase also raised the need to improve the connections to/from Rome. Although the distance between the airport and the local railway station is just a 900 m beeline (Figure 1), the opportunity of a direct link was never exploited.

Figure 1. Aerial view of Ciampino airport and surrounding area.

The local railway line serving Ciampino is a major link to commute from Rome to the densely populated Castelli area (a conurbation of more municipalities accounting for around 300,000 inhabitants, of which Ciampino is part), but unfit in its present form to supply a fast connection, specifically to the airport.

This means that the only option to reach the airport is rubber-tired, either by private cars or by transit. Several shuttle services to Rome (coaches and charter buses) operate daily, along with two regular bus lines introduced in 2010 by the Rome transit company and those supplied by the regional transit operator which connects the airport both to the local railway station and the terminus of Rome metro line A [2]. However, the modest performance (headways and on-board comfort) makes the overall public supply less appealing if compared to the shuttle services. As for any international airport, rental, car sharing and regular taxi services are also available. The overall parking supply is composed of 1573 stalls.

3.2. Land Use around the Airport

Ciampino airport is located in the eponymous town (around 40,000 inhabitants), initially conceived and designed as a "garden city" in the second decade of the 1900s, to accommodate the airport staff. This original core is still visible in Figure 1, in the area with the radial arrangement of streets and the central square close to the railway station. Nevertheless, the town has been always considered a satellite community of Rome, due to its proximity (15 km), more affordable housing opportunities, and fast connections thanks to two major arterials (the Tuscolana-Anagnina and Appia roads, the latter with average daily traffic of 28,000 vehicles [48]) and railway lines, and eventually a metro line.

From the 1960s on, housing demand increased up to a point that illegal constructions became structural, giving rise to several residential areas, even just outside the airport area limits (Figure 2), with high risks in case of accidents [49].

Figure 2. Proximity of the runway to the built environment and its quality.

As a result, land use is a mix of residential and tertiary functions, cultivated and natural areas, and other large facilities such as Rome's racecourse, all virtually surrounding the runway (Figure 1). Thus, when, at the beginning of the 2000s, low-cost companies started operating in Ciampino and the flight volume fast increased, the conflict became clear: air operations were not compatible with such a dense urban settlement. Unsustainable noise levels compelled air traffic authorities to cancel operations during nighttime, creating a major obstacle for the airport's new Master Plan approval. However, setting a cap on night operations is not enough since the building stock close to the runway is a mix of residences and public facilities and among these several public schools. This called for a specific "Noise Reduction and Abatement Plan", for which a set of 27 sensitive school areas (including nurseries and kindergartens) have been surveyed with a view to a renovation program to adapt windows and doors [50].

Additional environmental concerns are also raised by the airport's proximity to some local Natura 2000 network zones, whose specific wildlife and habitat safeguard calls for more constraints, as well as to the several rural landmarks and local rural landscape preserved by the Cultural and Archeological Heritage regulations.

If the importance of this airport is considered in the Ciampino area (volume of air traffic, staff attracted, real estate assets relevance) its "urban" role is clear, for better and for worse. The airport originated the settlement, generated opportunities boosted by the proximity to Rome, shaped the urban form in a very compact pattern, and determined an interruption in the land use (Figure 1). This urban system (airport *plus* town or vice-versa) is now characterized by high levels of road congestion along the arterials as a consequence of such density, the illegal buildings and the poor transit supply. It would be overly simplistic to consider Ciampino airport as just a transportation node. There are several definitions of transportation nodes, the common feature being that each node represents an intersection of several transportation lines or a point where a user can enter the transportation network [51]. Implicitly, multimodality increases the quality of the node and Ciampino in its role of interchange between air and surface modes represents an added value to the area where it is located. Consequently, given the strict interrelation between the airport and its surroundings, the impacts of the transportation supply on this urban system cannot be fully assessed if considering the contributions of surface and air modes' emissions separately but calls for a more comprehensive assessment.

4. One Methodology and Two Procedures for a More Accurate Assessment

The reported facts clarify the research question about the need for a comprehensive assessment of the emissions generated by an airport surrounded by a high-density built-up area, in order to highlight the specific contributions of surface and air traffics, especially if the divergence among different regulatory tools (land use master plans, airport masterplans and local mobility plans) is to be reduced.

The methodology for this type of assessment relies on consolidated and specific procedures for the emission modeling for each type of traffic (which are usually applied separately), eventually merging and comparing the results (Figure 3).

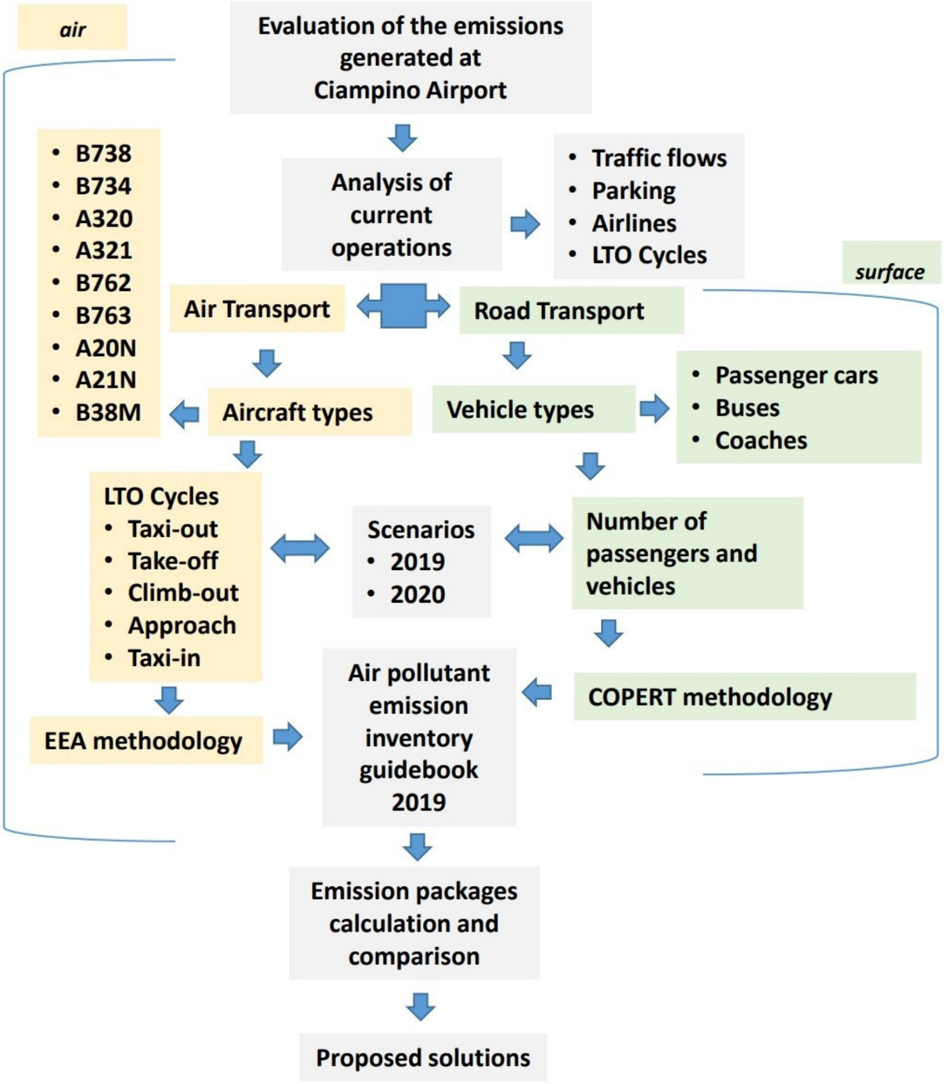

Figure 3. The methodology flowchart.

Although the modeling procedures are specific, airside and landside were considered as one single environment, i.e., the “Ciampino Envelope”, also in light of the low altitude where the LTO operations take place. The “envelope” was, thus, determined by considering the LTO cycle altitude (i.e., 3000 ft) and a 2.5-km radius surface catchment area so as to include in the calculation the road traffic generated by the two closest arterials. Data on both air and surface traffic were collected to “feed” the emission models quantifying the impacts on the Ciampino Envelope. Simulations were developed starting from the study scenarios (2019–2020) for each transport system but given the pandemic situation data and results for 2019 should be considered more significant and closer to normalcy.

To ensure consistency, models and simulations had a common ground, both relying on the EEA—European Environment Agency regulations (more specifically, the “EMEP / EEA air pollutant emission inventory guidebook 2019”), as further detailed.

4.1. Airside Emissions Simulation

As said, Ciampino operates both military, general aviation (including helicopters services) and commercial flights, with the latter accounting for the largest share, with an 18-gate passenger terminal available, processing 52,253 movements in 2019 (Table 1), virtually halved to 27,699 in 2020 [4,46,47].

The emission scenarios corresponding to such figures were built by computing the impact of air operations on the Ciampino Envelope occurring, as said, within 3000 ft of altitude, i.e., within the LTO cycle zone. The LTO cycle is composed of different phases (taxi-out, taxi-in, take-off, climb-out, approach and landing), the duration of each regulated by the International Civil Aviation Organization—ICAO standards. It is here to be reminded that LTO is a different parameter from "aircraft movement", the latter simply representing a landing or take-off of an aircraft at an airport, i.e., a departure or an arrival.

Within LTOs, duration is important as it describes how long the engine operates under that given situation, thus the specific engines' thrust required, the related amount of fuel consumed, and which are the types and amount of pollutants consequently emitted. For example, during take-off carbon dioxide may be prevalent [52], but ultrafine particles are not negligible, with studies demonstrating that the impact is still detectable at 10 km from the airport premises [53]. In other words, each LTO stage is different not only because its duration varies, but also because of the specific thrust each aircraft's engines need to complete it (for example, typical engine power settings are: Idle (taxi in) 7%; Take-off 100%; Climb-out 85%, Approach (approach and landing) 30% [54].

For the case in hand, data for the taxi-in and taxi-out durations have been initially retrieved by the EEA database [55] for the 2019 operations and further refined via a specifically built dataset, fed with the 2019 and 2020 data from the two most popular internet-based services providing real-time commercial aircraft flight tracking data (https://www.flightradar24.com and https://it.flightaware.com). The spreadsheets, thus created, enabled the emissions calculation according to the EEA methodology [56], which stems from the standard relation where emissions are the product of the Emission Factor (EF) times the Activity Data (AD) coefficients. In detail, EF is a coefficient specific for each pollutant, whereas AD represents the amount of pollutant emissions generated by a given human activity [55]; in this case, the fuel consumption represented here the AD in the energy sector and EF the mass of pollutants emitted per unit of fuel consumed

For the different types of aircraft operating at a given airport on a yearly basis, such standard relation becomes:

$$E_p = \sum_a AR_{fj} \times EF_{pj} \tag{1}$$

where

E_p is the annual pollutant emission for each cycle, in this case, the LTOs, and

AR_{fj} is the fuel consumption for each flight phase, type of flight, and *j*-type of aircraft

EF_{pj} is the pollutant emission factor for the corresponding flight phase, type of flight and *j*-type of aircraft.

For the Ciampino Environment, (1) was used to calculate the total amount E_{ij} of the *i*-pollutant emitted by the *j*-aircraft during the LTO cycle, as:

$$E_{ij} = \sum_k (TIM_{jk} \times FF_{jk} \times EI_{ijk} \times NE_j) \tag{2}$$

with

TIM_{jk} is the time in mode for the *k*-phase and the *j*-type aircraft,

FF_{jk} is fuel flow during the *k*-phase for the *j*-type aircraft

EI_{ijk} is the emission factor for the *i*-pollutant, in the *k*-phase for the *j*-type aircraft

NE_j is the number of engines installed in the *j*-type aircraft.

Thus, equations (1) and (2) quantify the pollutants released into the environment by each type of aircraft, during each flight phase. However, when calculating equation (2), the engines' emission factor is dependent on the fuel consumed during each LTO cycle phase. This can be processed via Eurocontrol's Advanced Emission Model—AEM [57]. AEM enables us to compute the amount of fuel burnt and related exhaust emissions from specific flight profiles (fuel flow rates and emissions of a given engine for both the LTO cycle and Climb, Cruise, Descent—CDD phases). These data are available at PRISME, a proprietary database that collects data on air traffic in the Instrument Flight Rules—IFR flight areas, and consistent with the information by the ICAO Engine Exhaust Emissions Data Bank [58], further used. Equation (2) calculations require an additional dataset to be built, concerning the aircraft fleets that actually operated in Ciampino in 2019 and 2020. This dataset was specifically built by merging data from airlines' records, the airport's official schedule and the above-mentioned web providers of real-time and historical flight tracking data (i.e., *Flightaware* and *Flightradar24*). In such data collection, any operational aircraft was registered along with the related registration code, installed engine features and technical specifications. This task is important as the same type of aircraft may have installed different engine configurations, thus releasing different amounts of pollutants. Ciampino was no exception: for example, the same type of Airbus aircraft (A320) was operated by two different airlines, in each case with different engine types (V2527-A5 and CFM56-5B4/P). This is reported in Table 2, where typical information and data collected to describe the monthly average traffic are shown, taking September 2021 as an example. In Table 2, the typical standard seat capacity is also provided, just to describe the type of achievable payload; however, to this end, it is to be noted that the seat configuration for each type of aircraft might markedly change according to the airline standards.

Table 2. Typical data collected to describe monthly average traffic, September 2021 as an example.

Aircraft Type	Movement (Unit)	Frequency (%)	Fuel Burnt Per Single LTO Cycle (kg)	Engine	Standard Seat Capacity (Units for Typical Accommodation Configuration)
B738	560	79.2	770	CFM56-7B26	162
B734	9	1.3	775	CFM56-3C1	146
B762	9	1.3	1269	CF6-80A	244
B763	8	1.1	1335	CF6-80C2B2F	269
A20N	2	0.3	526	PW1127G-JM	150-180
A21N	4	0.6	652	PW1133GA-JM	180-220
B38M	10	1.4	630	LEAP-1B27	162-178
A320	63	8.9	747 713	V2527-A5 CFM56-5B4/P	150
A321	42	5.9	900	V2533-A5	185

Fuel parameters to be entered in equation (2) were collected using data on fuel consumption provided by the ICAO Engine Certification Specification, obtained from different databases, for example, the mentioned ICAO Engine Exhaust Emissions Data Bank, based on various recorded data of different aircraft types and possible engine configurations. Once the data collection was completed and the spreadsheets for the Ciampino operations filled in, the EEA software [55] was used to model the emission packages. By selecting the aircraft type, engines installed, the infrastructure considered, the emission factors, and the fuel consumption pattern (in kg mass of fuel burned per second for each engine) it was possible to calculate the emissions of CO_2, water vapor, NO_x, SO_x, unburnt hydrocarbons, CO, VOCs, and other organic gases for the whole fleet of aircraft operating in Ciampino in 2019 and 2020, as reported in Section 5.

4.2. Landside Emissions Simulation

Landside emission modeling requires proper knowledge of the mix of vehicles accessing and leaving the airport area, to create emission scenarios comparable to those associated with the airside traffic. The model used to this end was the well-known COPERT

[59], not only because of its reliability but also because it is included within the EEA pollutant emission inventory methodologies already adopted for the airside study [59,60].

The first step was to understand Ciampino Envelope's surface accessibility. As stressed in the MTPL and anticipated in Section 3.1, direct and fast access to Ciampino airport, although close to the railway, is viable only by rubber-tired modes, i.e., private cars and commercial transfer services, mostly chartered buses and coaches, taxis and rentals. This explains the modal share in Figure 4 with more than 50% of passengers and visitors reaching the airport by these services and the availability of around 1600 parking stalls for private cars, taxis and powered two-wheelers (distributed in several parking facilities close to the passenger terminal) mentioned in Section 3.2.

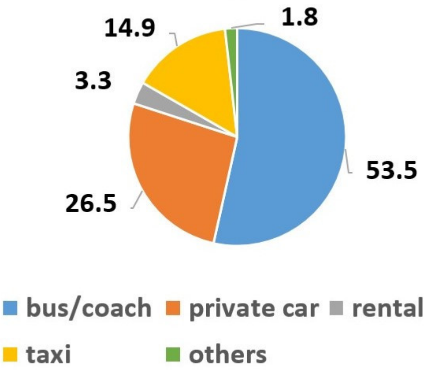

Figure 4. share (percentage of total passengers) of the means of transportation used by passengers to/from the airport.

The modal share and the yearly passenger demand were the starting points to build the accessibility scenarios to determine the amount of vehicles and their consequent polluting impact on the area. More specifically, the 2019 and 2020 annual demand (5,879,496 and 1,187,967 passengers, respectively [44]) was first subdivided according to the modal percentages. The passenger cars, rentals and taxi shares were initially associated with different occupancy rates, i.e., 1.25, 1.5, 2 and 3. It should be noted that 1.25 and 1.5 are average European values [61] and typical of Rome's mobility patterns. The reliability of these facts was corroborated by specific surveys at the airport parking areas where, along with data related to the passengers' occupancy, additional data on vehicle occupancy durations at parking were collected. The surveys also included traffic counts on the arterials accessing the Ciampino Envelope. The survey confirmed the low occupancy rates for passenger cars (1.25 and 1.5) versus the full occupancy of buses and coaches (which will be assumed as a reference in the emission calculations for this type of vehicle).

Data on 2020 in Table 3 stress the poor significance of the pandemic scenario, i.e., its exceptionality, in terms of vehicular traffic in general. Even if considering the most "burdened" situation, i.e., 424,817 vehicles associated with the 1.25 occupancy rate in 2020, this corresponds to average daily traffic of slightly more than 1100 vehicles, not even comparable with the average pre-pandemic daily traffic recorded on the arterials, reported in Section 3.2.

Table 3. Passenger car traffic scenarios according to occupancy rates, for years 2019 and 2020.

Scenarios		Vehicle Types (Units)			
Year	Occupancy Rate	Taxi	Private Car	Rental	Total
2019	1.25	700,836	1,246,453	155,219	2,102,508
	1.5	584,030	1,038,711	129,349	1,752,090
	2	438,022	779,034	97,012	1,314,068
	3	292,015	519,355	64,674	876,044

2020	1.25	141,606	251,849	31,362	424,817
	1.5	118,005	209,874	26,135	354,014
	2	88,504	157,406	19,601	265,511
	3	59,002	104,937	13,068	177,007

The traffic scenarios thus built need to be further processed in order to generate data to run the COPERT model. To this end, the vehicular fleets from Table 3 were associated with the EURO classes, so as to describe the fleets segmentation according to EURO compliance and emission class. Data from Table 3 were matched with the data on the EURO compliance of the total vehicular fleet registered in Rome [62,63]. This enabled us to highlight that, although 43.8% of the private cars are EURO V and VI compliant, there is still a significant 18.3% of EURO 0 to II compliant ones, still circulating. In turn, rentals and taxis are virtually all the newest and cleanest generation vehicles. The same applies to coaches, being 56% EURO V and 44% EURO VI. On the contrary, buses are mostly diesel-fueled, more or less equally divided into the EURO 0—III and EURO IV-VI classes.

The implication of such fleets' composition in terms of emissions generation is particularly severe if the results of Table 4 for the 2019 scenarios are considered. In this case, the 1.25 and 1.5 occupancy-rate scenarios (which correspond to the actual surveyed situations) imply a fleet from 320,000 to 385,000 highly polluting vehicles still circulating.

Table 4. Passenger car traffic scenarios according to EURO-compliance, 2019 and 2020.

Scenarios		**Vehicle Types per EURO-Compliance (Units)**			
Year	**Occupancy Rate**	**0-II**	**III-IV**	**V-VI**	**Total**
2019	1.25	384,759	792,646	925,103	2,102,508
	1.5	320,633	660,538	770,919	1,752,090
	2	240,474	495,403	578,189	1,314,068
	3	160,316	330,269	385,460	876,044
2020	1.25	77,741	160,156	186,920	424,817
	1.5	64,784	133,463	155,767	354,014
	2	48,589	100,097	116,825	265,511
	3	32,392	66,732	77,883	177,007

All the above data enabled us to run COPERT and obtain a snapshot of the emissions generated within the Ciampino Envelope by surface traffic, elaborated and compared with the airside traffic in the next Section.

5. Airside and Landside Emissions

The results from the simulations on airside and landside emissions enabled us to outline the quantity of the pollutants emitted by the air and surface transportation systems within the Ciampino Envelope. They also enabled us to compare the contribution of each system and eventually respond to the initial research question. However, the quantification of the impacts of each system raises some noteworthy elements of discussion, as further presented.

5.1. The Airside Contribution

According to the above-mentioned procedure, emissions estimated for 2019 are presented in Table 5 (and it is here to be reminded that these are the emissions just considered within the airport Envelope, as defined in Section4). In general, for the overall 26,128 LTO cycles operated that year, it can be observed that major contributions are associated with two specific types of aircraft, B738 and A321, and the frequency they operate (Tables 2 and 5). This might debunk the myth that larger aircraft, *per se*, pollute more. In turn, if the amount of fuel burnt is taken into consideration, the most consuming ones are still the B762s and B763s, i.e., cargo aircraft with a larger body and greater weight than the above two, as well as a longer mileage range (Tables 2 and 5). At the same time, the B762s and B763s appear to pollute more considering each LTO cycle.

It should also be mentioned that pollutants are mostly emitted when the combustion process is not completed or does not occur properly; for example, hydrocarbons characterize rather poor combustion. This shifts the focus to other operational fields, typically that of maintenance.

Table 5. Pollutants emitted per aircraft type and LTO cycles, 2019, determined by the EEA emission calculator.

Aircraft Type	Body	Mileage Range	Total LTO Cycles (Unit)	Pollutant Emitted, Mass (kg)			
				CO_2	CO	HC	NO_x
B738	narrow	Medium	20,694	50,162,982	102,827	10,569	243,628
B734	narrow	Short/ Medium	333	811,419	2628	133	3025
B762	wide	Medium/ Long	333	1,329,623	3538	778	7193
B763	wide	Medium/ Long	296	1,243,330	2788	240	5187
A20N	narrow	Short/ Medium	74	122,492	401	6	429
A21N	narrow	Short/ Medium	148	98,952	349	3	248
B38M	narrow	Short/ Medium	370	733,816	1225	55	4433
A320	narrow	Short/ Medium	1374	3,232,513	5438	70	13,974
			954	2,144,078	5573	1110	10,342
A321	narrow	Short/ Medium	1552	4,399,667	5011	89	25,741
Total LTO cycles and emissions			26,128	64,278,872	129,778	13053	314,200

For the sake of brevity, the 2020 emission scenario will not be reported here, since it cannot be significant, clearly reflecting the drastic traffic decrease (just 13,860 LTO cycles) caused by the Covid-19 pandemic. Emissions figures are evidently smaller but cannot be considered performance target values or a general goal in the pollution mitigation process or in any related policy, the economic and social tolls paid being too high [64,65].

Figures from Table 5 are affected by the duration of the LTO two variable phases, i.e., the taxi-out and taxi-in ones. The EEA software computes both according to three different parameters:

- The average annual times at Ciampino airport;
- The ICAO default time, i.e., a reference standard time;
- The average annual timing of the 25 busiest airports (Table 6).

As a matter of fact, the total taxi-out phase lasted, in 2019, 666s, not significantly far from the worldwide 25 busiest airports' reference value, and the taxi-in phase appears to be even closer. Intuitively, the implications from this comparison are not negligible, Ciampino's magnitude of operations being much smaller than in any of those 25 airports.

As for maintenance, this shifts the focus elsewhere, i.e., in the field of delays, with aircraft on hold with the engines running and emitting more than under regular schedules.

Table 6. Taxi-out and taxi-in phases duration in the 2019 emission scenario.

Parameters	Taxi-Out (Second)	Taxi-In (Second)
Average Ciampino	666	399
ICAO	1140	420
25 busiest airports	890	413

5.2. The Landside Contribution

The emissions generated from surface traffic in 2019 are reported in Table 7. The above-mentioned considerations as to the poor relevance of the estimations for 2020 are valid in this case too, with the reduction in car traffic having been even more severe due to the Spring 2020 total lockdown and the shorter ones occurred later in the Fall (on the contrary, flights never stopped completely, especially those operating cargo).

Table 7. Pollutants emitted per vehicle type and prevalent occupancy rate, 2019, determined by the COPERT model.

		Pollutants Emitted Mass (kg)			
Vehicles	**Occupancy Rate**	CO_2	**CO**	PM_{TSP}	NO_x
Passenger cars (gas)	1.25	72,770	1521	14	202
	1.5	60,641	1268	11	168
Passenger cars (diesel)	1.25	69,933	15	22	236
	1.5	58,277	12	18	196
Passenger cars (CNG—Compressed Natural Gas bifuel)	1.25	2599	11	1	0.42
	1.5	2925	9	0.62	0.41
Passenger cars (LPG—Liquefied Petroleum Gas)	1.25	10,655	70	2	17
	1.5	8879	59	2	14
Passenger cars (hybrid)	1.25	1070	0,17	0.27	0.17
	1.5	892	0,14	0.22	0.15
Bus (diesel)		12,277	17	4	65
Bus (CNG)		538	0,43	0.05	4
Coaches		58,637	57	12	100
Total emissions (occupancy rate 1.25)		228,479	1692	55	625
Total emissions (occupancy rate 1.5)		203,066	1423	48	548
Total emissions (bus and coaches)		71,452	74	16	169
Total emissions (occupancy rate 1.25 + buses and coaches)		299,931	1766	71	794
Total emissions (occupancy rate 1.5 + buses and coaches)		274,518	1497	64	717

Focusing on CO_2, the amount of emissions produced by gas-fueled cars with a 1.25 occupancy rate (72,270 kg) almost equates to that from buses and coaches (71,452 kg). If the amount of highly polluting vehicles still circulating is considered (Euro 0 to II in Table 4) along with the very low, but realistic, 1.25 occupancy rate, it is clear that the combination of these two phenomena is extremely detrimental and certainly contributes to the magnitude of such emission. The unsustainability of solo driving is even more evident if the 53.5% bus and coaches share in the modal split is considered. However, the low occupancy rate, in this case, appears to be an airport-specific travel option, being generated mostly by passengers using chauffeured services to reach Ciampino. In Rome, for medium to long distances, this type of rental with a driver is a competing option for taxis due to its higher comfort, being the cost equal (and even lower). In terms of occupancy and traffic generation, this becomes one more detrimental factor as most services are one-way, with empty returns.

Trends observed for the other pollutants are in line with usual emission patterns for urban traffic, and especially for the total suspended particulate matter (PM_{TSP} in Table 7) mostly generated by diesel passenger cars [59,60].

Thus, the results from Table 7 were expected since coherent with the local emission trends and registered fleet composition. The COPERT simulation provided just a close snapshot of the emissions packages within the Ciampino Envelope stressing the well-known problems behind: no high capacity, rail supply to reach the airport; too high passenger cars' share; no suitable transit supply. The PRMTL solutions described in the introduction are all valid, but if analyzed in light of the amount of pollution generated by air traffic, as elaborated in the next section, they call for more policy implications.

6. Discussing Air-vs-Surface Policy Implications

The "car-vs-aircraft" comparison clearly shows that air traffic is much more polluting than rubber-tired modes. One example for all: CO_2 emissions yearly generated by the road system (228,479 kg, in the 1.25 occupancy rate scenario) are certainly marginal if compared to those generated by all LTOs (64,278,874 kg) in the same period. Comparative analyses for the other pollutants stress a similar difference in magnitude. It is also to be noted that the airside emission package does not include the contribution of the air terminal ground functions (handlings, ramp operations, commercial services, etc.), which was estimated by the Airport Authority in additional 2,779,000 kg of CO_2 and 172,000 tons NO_X for 2018 [47].

If the figures reported the response to the research question by identifying air traffic as a major polluter, and the facts provided in Tables 5 and 7 serve as a reference for assessments in airports similar to Ciampino, all of the above also paves the way for a discussion on the policy implications, as just stressed.

The first issue concerns the extent or the scope of typical directions of urban mobility plans. If rebalancing passenger cars share in favor of public transport or shared modes is imperative [1], and more in general rubber-tired modes in favor of rail, in sensitive areas such as airports this might not be sufficient to reduce the local emissions generation and results might be modest.

In other words, if the goal is to reduce emissions generated by passenger cars, the urban mobility plans, and in this case the MTLP's measures, in favor of transit and multimodality to access the airport are leading in the right direction. Nevertheless, if the goal is to reduce transport emissions in general, then the lesson learned by the Ciampino case shows that actions must be targeted to control aircraft movements below 3000 feet, rather than road traffic, given the marginal role played by the latter.

When shifting to air operations, several options are presented in literature and practice. For example, if Table 6 is considered, reducing delays in the taxi-out operations would be beneficial as it would limit aircraft engines running and emitting while on hold, and more in general this would be feasible for any taxiing operations. One more option to consider is reducing engines' thrust setting during take-off operations, as reported in a study on London Heathrow operations [66]. However, optimizing thrust means creating a balance between safety and environment, and implies actions on Take-Off Weight—TOW, which would require the involvement of airlines. Other options could be applied in the taxiing operations: reducing thrust, e.g., the Single-Engine Taxiing mode (i.e., taxiing relying on half of the aircraft engines); dispatch towing (i.e., the aircraft is towed on the taxiway with the engines off, with just the heating/cooling needed for the engines); or eventually resorting to electrification for the landing gear [67]. For all, again the carriers' involvement would be necessary.

This brings back the issue raised in the introductory parts, i.e., the limitations of urban mobility plans (such as the MTPL) when dealing with air companies, these actors being “supralocal” and, unlike rail operators, less rooted in the territory and more difficult to attract in the local participation process. This problem is exacerbated in the case of low-cost carriers, constantly attracted by the opportunities of opening new routes and therefore extremely fast in “moving out” from one airport to another.

One more area of intervention could be in the field of infrastructural improvements. By optimizing the apron-runway connection it is possible to minimize aircraft overall ground movements, highly beneficial at take-off especially. Again, this may represent one more limitation in the urban mobility plans given their low-cost “nature”, which hardly includes heavy interventions on infrastructures and even less on airport ones.

The common trait is that none of the above-mentioned solutions are not compatible with the urban mobility plans’ typical horizons. Within this plan, for example SUMPs, fast interventions are most often pure regulatory, which in this case leaves the only option of air traffic limitation. This has been already enforced in Ciampino at night, to avoid noise, but certainly cannot be extended in day times so and simply.

Noise management, which is the “twin” problem of air emissions, and since longer considered a sensitive issue for the communities living close to airports, is still unsolved, which is one more lesson to consider. Like air emissions, regulations in this field are very strict. More specifically, regulations on noise mitigation associate land use with proposed aviation actions according to the level of aircraft noise and introduce restrictions (e.g., in the U.S, via the *Code of Federal Regulations part 150, Land Use Compatibility with Yearly Day-Night Average Sound Levels*, or in Europe through the *Regulation 598/2014* enforcing rules and procedures with regard to the introduction of noise-related operating restrictions). Acoustic recovery plans or simple noise measurement urban plans, in turn, establish limits for human activities and land use according to proximity to noise sources (typically airports). Eventually, the enforcement of mobility plans might require the management of noise impacts generated by a given (surface) infrastructural intervention via direct measurements and simulations. Additional supranational (e.g., from ICAO) or local rules or limitations might apply. However, a comprehensive assessment of all of the above, in general, is hardly carried out. Best practice and case stories show that there is no one-fits-all solution, the process being very challenging and strong involvement of the stakeholders much needed [68].

Eventually, it is to stress that the emission phenomena here analyzed are just restricted to Ciampino Envelope, but if such a disproportionate magnitude of the emissions produced by aircraft on their whole daily performance (i.e., thousands of miles) is considered the “Envelope” becomes larger and larger, and again not comparable to the restricted areas of influence associated with surface traffic (urban or regional levels).

7. Conclusions

The results above reported can be considered a scientific exploration in the emission assessment within surface transport policies, where air modes’ contributions in polluting are high but rarely considered, although standardized procedures enable us to determine the magnitude of this phenomenon.

Airport masterplans compulsorily address the emission problem, but especially for the facilities already operational, ground solutions are not fast to implement (towing, thrust management, delays reductions). In turn, affected communities can address the problem via urban regulatory tools (urban traffic plans, SUMPs, urban masterplans and the likes) but these are limited to surface traffic and thus ineffective, the actual solutions being beyond reach. Moreover, there often is no full knowledge of the magnitude of the emissions generated by air traffic compared to road traffic and providing evidence of that was the main goal of the present paper.

It is clear that multimodality as a concept in urban plans must be enlarged, also including air transport; likewise, for the associated participation process with the involvement of air carriers and air traffic managers to eventually find shared solutions.

One more contribution is to advance awareness and knowledge, which was the additional goal of this paper, when providing tangible facts about the emissions generated by the two types of traffic. By grasping the magnitude of the phenomena, it is possible to develop specific solutions (or at least to start the process to implement them, if the horizon is far), instead of proposing general traffic measures, effective, but more appropriate elsewhere. However, it is to be acknowledged that there are some limitations in describing the magnitude of the phenomena due to the difficulty to include all the traffic contributors, for example, surface heavy-duty vehicles, which usually require specific counts, since commercial traffic is usually not included in the general origin/destination traffic surveys (for example, in Italy, commercial traffic below 50 km distance is not included in the national statistics on traffic counts).

At the same time, more studies on the effects of the ground solutions for air traffic are needed to assess/at a larger scale the potential benefits in terms of emissions mitigation and the first applications from the follow-up of this research [67] in this direction are providing promising results and further validating the results described in this paper.

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References

1. Vuchic, V.R. Transport systems and policies for sustainable cities. *Therm. Sci.* **2008**, *12*, 7–17. https://doi.org/10.2298/TSCI0804007V.
2. Regione Lazio, Piano Regionale della Mobilità, dei Trasporti e della Logistica. Available online: https://www.pianomobilitalazio.it/ (accessed on 22 March 2022).
3. Rome Municipality. II turismo a Roma, anno 2019. Available online: https://www.comune.roma.it/web-resources/cms/documents/Il_turismo_a_Roma_2019_new.pdf (accessed on 14 May 2022).
4. Ministero delle Infrastrutture e della Mobilità Sostenibili. *Conto Nazionale delle Infrastrutture 2019–2020*; Istituto Poligrafico e Zecca dello Stato: Rome, Italy, 2021; pp. 219–229.
5. Popescu, F.; Ionel, I.; Talianu, C. evaluation of air quality in airport areas by numerical simulation. *Environ. Res. Eng. Manag. J.* **2011**, *10*, 115–120. https://doi.org/10.30638/EEMJ.2011.016.
6. Corazza, M.V.; Musso, A. Improving Urban Mobility Management: The Rome Case. *Transp. Res. Rec.* **2006**, *1956*, 52–59. https://doi.org/10.1177/0361198106195600107.
7. Hirst. M. *The air transport system*. Woodhead Publishing: Cambridge, United Kingdom, 2008; pp. 120–121.
8. Zhou, Y.; Jiao, Y.; Chen, D.; Huang, C.; Wei, P.; Li, S.; Cheng, S. Improved estimation of air pollutant emissions from landing and takeoff cycles of civil aircraft in China. *Environ. Pollut.* **2019**, *249*, 463–471. https://doi.org/10.1016/j.envpol.2019.03.088.
9. Tokuşlu, A. Calculation of Aircraft Emissions During Landing and Take-Off (LTO) Cycles at Batumi International Airport, Georgia. *Int. j. environ. Geoinformatics* **2021**, *8*, 186–192. https://doi.org/10.30897/ijegeo.836780.
10. Galant-Gołębiewska, M.; Jasiński, R.; Ginter, M.; Maciejewska, M.; Nowak, M.; Kurzawska, P. Methodical aspects of the LTO cycle use for environmental impact assessment of air operations based on the Warsaw Chopin airport. *Aviation* **2021**, *25*, 86–91. https://doi.org/10.3846/aviation.2021.14972.
11. Liu, H.; Tian, H.Z.; Hao, Y.; Liu, S.; Liu, X.; Zhu, C.; Wu, Y.; Liu, W.; Bai, X.; Wu, B. Atmospheric emission inventory of multiple pollutants from civil aviation in China: Temporal trend, spatial distribution characteristics and emission features analysis. *Sci. Tot. Env.* **2019**, *648*, 871–879. https://doi.org/10.1016/j.scitotenv.2018.07.407.
12. Lu, C.; Liu, H.; Song, D.; Yang, X.; Tan, Q.; Hu, X.; Kang, X. The Establishment of LTO Emission Inventory of Civil Aviation Airports Based on Big Data. *IOP Conf. Ser.: Earth Environ. Sci.* **2018**, *128*, 012069. https://doi.org/10.1088/1755-1315/128/1/012069.
13. Yu, J.; Jia, Q.; Gao, C.; Hu, H. Air pollutant emissions from aircraft landing and take-off cycles at Chinese airports. *Aeronaut. J.* **2021**, *125*, 578–592. https://doi.org/10.1017/aer.2020.126.
14. Liao, L.; Fan, Y.; Wang, C.; Wang, Z. Emissions from intercity aviation: An international comparison. *Transp. Res. D: Transp. Environ.* **2021**, *95*, 102818. https://doi.org/10.1016/j.trd.2021.102818.
15. Lawal, A.S.; Russell, A.G.; Kaiser, J. Assessment of Airport-Related Emissions and Their Impact on Air Quality in Atlanta, GA, Using CMAQ and TROPOMI. *Environ. Sci. Technol.* **2022**, *56*, 98–108. https://doi.org/10.1021/acs.est.1c03388.

16. Stettler, M.E.J; Eastham, S.; Barrett, S.R.H. Air quality and public health impacts of UK airports. Part I: Emissions. Atmos. *Environ.* **2011**, *45*, 5415–5424. https://doi.org/10.1016/j.atmosenv.2011.07.012.
17. Postorino, M.N. Environmental effects of airport nodes: A methodological approach. *Int. J. Sustain. Dev. Plan*. **2010**, *5*, 192–204. https://doi.org/10.2495/SDP-V5-N2-192-204.
18. Masiol, M.; Harrison, R.M. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review. *Atmos. Environ*. **2014**, *95*, 409–455. https://doi.org/10.1016/j.atmosenv.2014.05.070.
19. Liu, Y.; Elham, A.; Horst, P.; Hepperle, M. Exploring Vehicle Level Benefits of Revolutionary Technology Progress via Aircraft Design and Optimization. *Energies* **2018**, *11*, 166. https://doi.org/10.3390/en11010166.
20. Ranasinghe, K.; Guan, K.; Gardi, G.; Sabatini, R. Review of advanced low-emission technologies for sustainable aviation. *Energy* **2019**, *188*, 115945. https://doi.org/10.1016/j.energy.2019.115945.
21. Jafari, S.; Nikolaidis, T. Thermal Management Systems for Civil Aircraft Engines: Review, Challenges and Exploring the Future. *Appl. Sci.* **2018**, *8*, 2044. https://doi.org/10.3390/app8112044.
22. Xu, H.; Gomez-Vega, N.; Agrawal, D.; Barrett, S. Higher thrust-to-power with large electrode gap spacing electroaerodynamic devices for aircraft propulsion. *J. Phys. D: Appl. Phys.* **2020**, *53*, 025202. https://doi.org/10.1088/1361-6463/ab4a4c.
23. Freeman, S.; Lee, D.S.; Lim, L.L.; Skowron, A.; De León, R.R. Trading off Aircraft Fuel Burn and NOx Emissions for Optimal Climate Policy. *Environ. Sci. Technol*. **2018**, *52*, 2498–2505. https://doi.org/10.1021/acs.est.7b05719.
24. Skowron, A.; Lee, D.S.; De León, R.R.; Lim, L.L.; Owen, B. Greater fuel efficiency is potentially preferable to reducing NO_x emissions for aviation's climate impacts. *Nat. Commun.* **2021**, *12*, 564. https://doi.org/10.1038/s41467-020-20771-3.
25. Saleem, A.; Karimi I.A.; Farooq, S. Estimating NOx emissions of useful two-fuel blends from literature data, *Fuel*. **2022**, *316*, 123213. https://doi.org/10.1016/j.fuel.2022.123213.
26. ENAV. Free Route and A-CDM. Available online: https://www.enav.it/en/innovation/free-route (accessed on 22 May 2022).
27. Burbidge, R. Adapting aviation to a changing climate: Key priorities for action. *J. Air Transp. Manag.* **2018**, *71*, 167–174. https://doi.org/10.1016/j.jairtraman.2018.04.004.
28. Efthymiou, M.; Papatheodorou, A. EU Emissions Trading scheme in aviation: Policy analysis and suggestions. *J. Clean. Prod*. **2019**, *237*, 117734. https://doi.org/10.1016/j.jclepro.2019.117734.
29. Dedoussi, I.C Implications of future atmospheric composition in decision-making for sustainable aviation. *Environ. Res. Lett.*, **2021**, *16*, 031002. https://doi.org/10.1088/1748-9326/abe74d.
30. Kshirsagar, P.; Ewanchuk, J.; Kheraluwala, M. Next Generation of Robust Aviation Electrification—Challenges and Opportunities. In Proceedings of 2021 IEEE International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 11–16 December 2021, pp. 31.5.1–31.5.4. https://doi.org/10.1109/IEDM19574.2021.9720665.
31. Zhang, J.; Roumeliotis, I.; Zolotas, A. Sustainable Aviation Electrification: A Comprehensive Review of Electric Propulsion System Architectures, Energy Management, and Control. *Sustainability* **2022**, *14*, 5880. https://doi.org/10.3390/su14105880.
32. Schwab, A.; Thomas, A.; Bennett, J.; Robertson, E.; Cary, S. Electrification of Aircraft: Challenges, Barriers, and Potential Impacts; Technical Report for National Renewable Energy Lab: Golden, CO, USA, October 2021. https://doi.org/10.2172/1827628.
33. Bousse, Y.; Corazza, M.V.; Arriaga, D.S.; Sessing, G. Electrification of Public Transport in Europe: Vision and Practice from the ELIPTIC Project. In Proceedings of 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I and CPS Europe), Palermo, Italy, 12–15 June 2018, 8494518. https://doi.org/10.1109/EEEIC.2018.8494518.
34. Airport Carbon Accreditation. Airports addressing their CO2 emissions. Available online: https://airportco2.org/actions-that-reduce-co2.html (accessed on 23 May 2022).
35. Dube, K. Climate Action at International Airports: An Analysis of the Airport Carbon Accreditation Programme. In *Sustainable Development Goals for Society Vol. 2. Sustainable Development Goals Series;* Nhamo, G., Chikodzi, D., Dube, K. Eds. Springer: Cham, Switzerland, 2021, pp. 237–251. https://doi.org/10.1007/978-3-030-70952-5_16.
36. Aeroporti di Roma. Fiumicino and Ciampino airports are the first in Europe to achieve the airport carbon accreditation 4+. Available online: https://www.atlantia.com/en/w/fiumicino-and-ciampino-airports-are-the-first-in-europe-to-achieve-the-airport-carbon-accreditation-4-from-aci-europe-1 (accessed on 23 June 2022).
37. A Route to Net Zero European Aviation, Available online: https://www.destination2050.eu/wp-content/uploads/2021/02/Destination2050_ExecutiveSummary_Commitments-1.pdf (accessed on 23 June 2022).
38. European Commission, Directorate-General for Mobility and Transport, Directorate-General for Research and Innovation, *Flightpath 2050: Europe's Vision for Aviation: Maintaining Global Leadership and Serving Society's Needs*, Springer: Berlin/Heidelberg, Germany, 2011. https://doi.org/10.2777/15458.
39. Federal Aviation Administration. Next Generation Air Transportation System (NextGen). Available online: https://www.faa.gov/nextgen (accessed on 23 June 2022).
40. Becker,K.; Nam, T.; Kirby, M.; Mavris, D. Process for Future Aviation Environmental Impacts: A Surrogate Fleet Analysis Approach for NextGen. In Proceedings of the 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), Hilton Head, South Carolina, USA, 21–23 September 2009. https://doi.org/10.2514/6.2009-6934.
41. Fischer, T.B., González, A. Introduction to handbook on strategic environmental assessment. In *Handbook on Strategic Environmental Assessment*; Fischer, T.B., González, A., Eds. Edward Elgar Publishing: Cheltenham, UK, 2021, pp. 2–10.
42. Freestone, R. Baker, D. Spatial Planning Models of Airport-Driven Urban Development. *J. Plan. Lit.*, **2013**, *26*, 263-279. https://doi.org/10.1177%2F0885412211401341.

43. ENAC—Ente Nazionale Aviazione Civile, Aeroporti di Roma. *Aeroporto G.B. Pastine di Ciampino–Roma*, Aeroporti di Roma: Rome, Italy 2015
44. Associazione Italiana Gestori Aeroporti. Statistiche 2001–2020. Available online: https://assaeroporti.com/statistiche/ (accessed on 21 January 2022).
45. *Sustainability Report* 2020: Our Choices Of Sustainability; Aeroporti di Roma: Rome, Italy, 2021.
46. Aeroporti di Roma. Annual Report 2017. Available online: https://www.adr.it/documents/17615/13348669/Annual_Report_2017_ENG.pdf/bcbb964b-b5e4-4557-84c7-f78c837783a5 (accessed on 03 July 2022).
47. Aeroporti di Roma. Traffic data monthly report. Available online: https://www.adr.it/web/aeroporti-di-roma-en/bsn-traffic-data?p_p_id=1_WAR_trafficdataportlet&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&_1_WAR_trafficdataportlet_dataRif=202112&_1_WAR_trafficdataportlet_tabs1=CIA (accessed on 21 January 2022).
48. Centro di Monitoraggio della Sicurezza Stradale della Regione Lazio—CEREM. L'incidentalità Stradale Sulla Sr 7 Dir/A Appia. Available online: https://ceremsslazio.astralspa.it/ceremss/PdfDossierStrade/SR_007_DIR_A_VIA_APPIA.pdf (accessed on 03 July 2022).
49. Magnani, N. Incendio Roma Ciampino. Available online: https://www.ilsussidiario.net/news/cronaca/2019/2/19/incendio-allaeroporto-di-roma-ciampino-ultime-notizie-scalo-evacuato-e-voli-fermi/1849788/ (accessed on 03 July 2022).
50. Aeroporti di Roma. Progress of Investments Plan. Available online: https://www.adr.it/documents/17615/14742848/2-ENG_Progress+of+investmentplan_2.pdf/37c5d7c1-4da6-4e8b-8c28-0722678f4f3b (accessed on 03 July 2022).
51. Institute of Transportation Engineers; Meyer M.D. *Transportation Planning Handbook*; Wiley: Hoboken, NY, USA, 2016, pp. 211–213.
52. Wei, Z., Han, X., Joon, C., Aaron, S. Calculation and Analysis of Aircraft Pollution Emissions in the Take-off Phase. *Lect. Notes Electr. Eng*. **2019**, *459*, 2001-2022. https://doi.org/10.1007/978-981-13-3305-7_161.
53. Hudda, N.; Gould, T.; Hartin, K.; Larson, T.V; Fruin, S.A. Emissions from an International Airport Increase Particle Number Concentrations 4-fold at 10 km Downwind. *Environ. Sci. Technol.* **2014**, *48*, 6628–6635. https://doi.org/10.1021/es5001566.
54. Khadilkar, H., Balakrishnan, H. Estimation of aircraft taxi fuel burn using flight data recorder archives. *Transp. Res. D: Transp. Environ.* **2012**, *17*, 532–537. https://doi.org/10.1016/j.trd.2012.06.005.
55. EEA—European Environmental Agency 2019, European Environmental Agency. A.3.a Aviation 2 LTO emissions calculator 2019. Available online: https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-a-aviation-1-annex5-LTO/view (accessed on 21 January 2022).
56. M. Winter, Rypdal, K. EMEP/EEA air pollutant emission inventory guidebook, Report 1.A3.a. Aviation 2019. Available online: https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-a-aviation/view (accessed on 21 January 2022).
57. Eurocontrol. Advanced emission model. Available online: https://www.eurocontrol.int/model/advanced-emission-model (accessed on 21 January 2022).
58. European Union Aviation Safety Agency—EASA. ICAO Aircraft Engine Emissions Databank. Available online: https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank (accessed on 21 January 2022).

59 Emisia, COPERT 5 Report; Available online: https://www.emisia.com/utilities/copert/versions/ (accessed on 18 August 2022).

60 Ntziachristos, L., Samaras, Z. EMEP/EEA air pollutant emission inventory guidebook, Report A.3.b.i-iv Road transport 2019. Available online: https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view (accessed on 21 January 2022).

61 EEA—European Environmental Agency, 2015 Data and maps, Occupancy rates of passenger vehicles. Available online: https://www.eea.europa.eu/data-and-maps/indicators/occupancy-rates-of-passenger-vehicles/occupancy-rates-of-passenger-vehicles-1 (accessed on 21 January 2015).

62 ACI—Automobile Club d'Italia, Annuario statistico 2021. Available online: https://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche/annuariostatistico/annuario-statistico-2021.html (accessed on 21 January 2022).

63 Comune di Roma, Mobilità e Trasporti 2021. Roma statistica. Available online: https://www.comune.roma.it/web/it/roma-statistica-mobilita1.page (accessed on 21 January 2022).

64 Le Quéré, C.; Jackson, R.; Jones, M.; Smith, A.; Abernethy, S.; Andrew, R.; De-Gol, A.; Willis, D.; Shan, Y.; Canadell, J.; et al. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nat. Clim. Change* **2020**, *10*, 647–653. https://doi.org/10.1038/s41558-020-0797-x.

65 Corazza, M.V, Moretti, L., Forestieri, G., Galiano, G. Chronicles from the new normal: Urban planning, mobility and land-use management in the face of the COVID-19 crisis. *Transp. Res. Interdiscip. Perspect.* **2021**, *12*, 100503. https://doi.org/10.1016/j.trip.2021.100503Get rights and content.

66 Koudis, G.; Hu, S.; Majumdar, A.; Jones, R.; Stettler, M. Airport emissions reductions from reduced thrust takeoff operations. *Transp. Res. D Transp. Environ*. **2017**, *52*, 15–28. https://doi.org/10.1016/j.trd.2017.02.004.

67 Di Mascio, P.; Corazza M.V.; Rosa N.R.; Moretti, L. Optimization of aircraft taxiing strategies to reduce air emissions at airport. *Sustainability.* **2022**, *14*, 9692. https://doi.org/10.3390/su14159692.

68 Leylekian, L. Preface. In *Aviation Noise Impact Management Technologies, Regulations, and Societal Well-being in Europe*. Leylekian, L. Alexandra Covrig, A., Maximova, A., Eds.; Springer: Cham, Switzerland, 2020, pp. vii–viii. https://doi.org/10.1007/978-3-030-91194-2.