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Optimization of Aircraft Taxiing Strategies to Reduce the Impacts of Landing and Take-Off Cycle at Airports

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Abstract: The increasing attention of opinion towards climate change has prompted public authorities to provide plans for the containment of emissions to reduce the environmental impact of human activities. The transport sector is one of the main ones responsible for greenhouse emissions and is under investigation to counter its burdens. Therefore, it is essential to identify a strategy that allows for reducing the environmental impact produced by aircraft on the landing and take-off cycle and its operating costs. In this study, four different taxiing strategies are implemented in an existing Italian airport. The results show advantageous scenarios through single-engine taxiing, reduced taxi time through improved surface traffic management, and onboard systems. On the other hand, operating towing solutions with internal combustion cause excessive production of pollutants, especially HC, CO, NOX, and particulate matter. Finally, towing with an electrically powered external vehicle provides good results for pollutants and the maximum reduction in fuel consumption, but it implies externalities on taxiing time. Compared to the current conditions, the best solutions ensure significant reductions in pollutants throughout the landing and take-off cycle (−3.2% for NOx and −44.2% for HC) and economic savings (−13.4% of fuel consumption).

Keywords: aircraft emissions; pollutants; fuel consumption; alternative taxiing modes; single-engine taxiing; dispatch towing

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Citation: Di Mascio, P.; Corazza, M.V.; Rosa, N.R.; Moretti, L. Optimization of Aircraft Taxiing Strategies to Reduce the Impacts of Landing and Take-Off Cycle at Airports. *Sustainability* **2022**, *14*, 9692. https://doi.org/10.3390/su14159692

Academic Editor: Firoz Alam

Received: 16 July 2022
Accepted: 4 August 2022
Published: 6 August 2022

1. Introduction

Air transport is one of the main economic activities associated with the development of a country, as it guarantees the mobility of goods and people. In the pre-COVID-19 period, aviation was responsible for about 2% of global greenhouse gas emissions produced by all economic sectors [1,2]. According to the pre-pandemic estimates of air traffic growth, the percentage incidence is expected to reach values between 10% and 15% by 2050 [3].

Aviation emissions are produced at two different levels:

1. At cruise altitudes (8–12 km) producing air pollution effects on a global scale and contributes to climate change [4,5];
2. At ground level, during the landing and take-off (LTO) cycle directly at the airport, contributes to the degradation of near-airport air quality [6,7].

The main pollutants produced by the operation of aircraft engines are hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM) [8]. Although emissions per flight hour have been deeply investigated and assessed [9,10] and different results require modification of used fuels and engine technologies, the operations during a complete LTO cycle require further investigation to be optimized. They refer to approach, taxi-in, taxi-out, take-off, and climb-out phases below the altitude of 3000 feet whose time in mode and percentage thrust are defined by ICAO [11]. The scientific literature focusing on ground-level emissions is vast [12–14] having also long acknowledged the relevance of exhausts generated by aircraft engines, along with the emissions from ground facilities and operations (from refueling to maintenance, to heating) and road traffic around the airport premises [15,16] and the strategic roles sustainable aviation fuels will play in the future [17–19]. All of the above becomes detrimental to the quality of life of the airport environments and the communities living nearby, with negative impacts also on public health [14,20–23]. Their emissions depend on the operational phase (approach, taxi-in, taxi-out, take-off, climb-out) [24]. The most significant parameters are the duration of each phase and the percentage of exploitation of the maximum thrust of the engine used in each phase. The taxiing phases (taxi-in and taxi-out) have a long duration with low operating thrust (7% each according to ICAO indications): the combustion occurs inefficiently, causing high quantities of emissions and producing negative effects on near-airport air quality. This has to be associated with the general fact that pollution is generated whenever the fuel combustion process is incomplete or not properly performed; typically, HC emissions are a sign of poor combustion. In the literature, studies concerning the effects of operating time during aircraft taxiing demonstrated the importance of this phase. In the USA between 2006 and 2007, taxiing time over 40 min increased by 20%, while in Europe an incidence of taxiing time of between 10% and 30% of the total flight time was assessed, resulting in a consumption of approximately 5–10% of the total fuel burned during the entire flight cycle [25]. Furthermore, Miller et al. [26] showed that the increase in the demand for air traffic leads to a higher rate of growth for taxiing time than for cruising time, due to the greater number of aircraft movements that cause on-ground congestion of the airport and overload of controllers [27]. Moreover, other studies assessed the emissions produced by an aircraft in varying taxiing modes; the following strategies were analyzed separately: single-engine taxiing [25], dispatch towing [25,26], onboard systems [28], and the optimization of surface traffic management [29]. However, most of these assessments define the inventory under standard operating conditions [30], without considering the impact of the real environmental conditions (air temperature and pressure).

Although the recent international climate agreements (from COP21 Paris 2015 to COP26 Glasgow 2021) do not provide for any regulation for greenhouse gas emissions from the transport sector, it is crucial to foresee an inventory of emissions produced by aircraft during the LTO cycle [31]. For this reason, this study aims to assess the emission scenario of an airport with the International Standard Atmosphere (ISA) according to the Airport Air Quality Manual [11] and Boeing Fuel Flow Method 2 (BFFM2) [32] to take into account the effect of environmental conditions. The ground handling phases are specifically analyzed to know the emissions distribution over the LTO phases [33]. Four different strategies for taxiing, (i.e., single-engine taxiing, dispatch towing, onboard systems, and optimization of surface traffic management) have been considered to assess different emission scenarios [34]. The results allowed the identification of the best strategy to reduce fuel consumption and air pollutants emissions.

The adopted methodology addresses the emission assessment, shortly described in Section 2.1, according to the above-mentioned ICAO's Airport Air Quality Manual, where a sensitive parameter, i.e., the fuel flow, is further specified by introducing additional criteria (related to temperature and pressure) to make it more consistent with the actual average environmental conditions, as elaborated in Section 2.2. This advances the usual approach for determining the fuel flow, just according to the ISA reference, and creates a more reliable simulation procedure. The methodology considers the most detrimental pollutants and specifically: HC, NO_x, PM, and CO_2. This updated procedure is applied to a middle-size Italian airport that cannot be disclosed for confidentiality reasons, located in a mixed land-use area; hereinafter called the Study Airport. The main performances of the Study Airport are elaborated on and reported in Section 3. These steps enable us to build different operational scenarios, where four different taxiing measures are considered to create a mitigation strategy for the air traffic emissions, as described in Section 4 and compared with the basic or business-as-usual operational scenario at the Study Airport.

2. Methods

2.1. Emissions Assessment

The ICAO Air Quality Manual [11] establishes three levels of assessment that enable the determination of inventories of emissions, corresponding to different accuracy levels: (i) simple, (ii) advanced, and (iii) sophisticated. Quantity and quality of available information and data dictate the level to select, which for the case in hand was the advanced one. The choice of the level of complexity of the calculation must be defined in advance, based on the input data and the reliability of the expected results. This study was carried out according to the advanced approach: it conjugates an excellent degree of detail and accuracy for the operating parameters to obtain reliable results. Therefore, Equation (1) gives the amount of consumed fuel (FC) during taxiing with all engines running (full engine taxiing, FET):

$$FC_{FET} = \sum_j FC_{j,FET} = \sum_j TIM_j \cdot FF_j \cdot N_j \quad (1)$$

where $FC_{j,FET}$ is the fuel consumption of the j-th aircraft during taxiing in FET conditions (kg), TIM_j is the time-in-mode for taxiing of the j-th aircraft (s), FF_j is the fuel flow for taxiing for each engine used on j-th aircraft (kg/s), and N_j is the number of engines used during taxiing of the j-th aircraft.

Equation (2) allows the calculation of the pollutant emissions during taxiing:

$$E_{i,FET} = \sum_j EI_{ij} \cdot \ FC_{j,FET} \quad (2)$$

where E_{ij} is the total emissions of the pollutant i produced by the j-the aircraft for one LTO cycle and EI_{ij} is the emission index for the pollutant i for each engine used on the j-th aircraft (kg/aircraft or #/aircraft).

TIM values were obtained through a monitoring activity of the real operating time inside the airport, based on the data recorded over 24 days of the busiest month of the year 2019 to take into account all traffic management surface scenarios and actual operation time typical of the reference airport herein not disclosed for privacy reason. Table 1 lists the taxiing TIM values calculated as the arithmetic average of the recorded data.

Table 1. Taxiing TIM values.

Phase	TIM (Minutes)
Taxi-in	6.3
Taxi-out	12.6

In Table 1 the values for a taxi-in and taxi-out are lower than the average values defined by ICAO (7 and 19 min, respectively).

2.2. Parameters for the Estimation of the Emissions

The fuel flow values (FF) and the emission indices of HC, CO, and NO_X were initially obtained through the Aircraft Engine Emission Data Bank (EEDB) [35], determined under ISA conditions during the aircraft engine test. These parameters were then corrected with the BFFM2 method, which uses scientific and empirical correlations to modify the FF values as a function of the airport's actual environmental conditions (air temperature and pressure). The PM emission indices relating to each phase of the LTO cycle were obtained with the First Order Approximation V.4.0 method [11]. This calculation system permits to obtain a plausible estimation of the concentration by mass of the particulate material (in terms of both volatile component and non-volatile). The CO_2 and SO_X emission indices are established according to [11] (3155 g/kg and 1 g/kg of fuel burned, respectively) [36,37].

2.3. Taxiing Strategies

This study analyzed the contribution of the taxi-in and taxi-out phases, maintaining the approach, take-off, and climb-out phases of the basic scenario. TIM values of the approach (4.0 min), take-off (0.7 min), and climb-out (2.2 min) phases have been defined according to the reference values provided by ICAO for the standard LTO cycle. Four different taxiing modes were studied:

1. Single-engine taxiing (SET);
2. Dispatch towing (APU);
3. Taxing with onboard systems (MES);
4. Reducing taxiing time (RED).

The results have been compared with those of the basic scenario (FET).

2.3.1. Single-Engine Taxiing

SET is the simplest operational mode of ground handling because it involves using half of the aircraft engines [38]. Therefore, the reduction in emissions corresponds to the number of pollutants that the turned-off engines would have produced during operation. This operating mode is not recommended in the case of sloping taxiways in adverse weather conditions that make the surface slippery or icy and where tight curves of small radius are because they would produce power overloads in the working engines. Furthermore, aircraft engines require heating and cooling time of 2 to 5 min: SET can be considered only if the duration of the taxiing phases exceeds the time necessary for the engines to warm up/cool down. In this study, the minimum time for considering this taxiing strategy is assumed equal to 5 min, as a precaution.

Equation (3) gives the fuel consumption in SET conditions (FC_{SET}):

$$FC_{SET} = \sum_j FC_{j,SET} = \sum \left[\frac{N_j}{2} \cdot TIM_j + \frac{N_j}{2} \cdot \min\{\ TIM_j\ ;\ 300\ \} \right] \cdot FF_{j,SET} \quad (3)$$

where $FC_{j,SET}$ is the fuel consumption of the j-th aircraft during taxiing in FET conditions (kg); $FF_{j,SET}$ is the fuel flow that measures the weight flow rate of fuel consumed by the engines of the j-th aircraft during taxiing (kg/s). According to Equation (3), all the engines of the j-th aircraft (N_j) operate for 5 min (engine warm-up/cooling time), while half of them are considered to be in operation during TIM_j (in seconds).

Equation (4) allows the calculation of emissions ($E_{i,SET}$) during SET conditions.

$$E_{i,SET} = \sum_j EI_{ij} \cdot\ FC_{j,SET} \quad (4)$$

2.3.2. Dispatch Towing

Dispatch towing is the operational towing of aircraft with a specific vehicle along the taxiways (from the parking stand to the runway threshold and vice versa): during the taxiing, the aircraft keeps the engines off, except for the heating/cooling time envisaged for the engines. The aircraft's power supply is guaranteed by the auxiliary power unit (APU). Although the emissions produced by aircraft engines are almost totally reduced, the emissions from APU and the towing vehicle must be considered. The contribution of towing vehicles is analyzed in three different scenarios, according to the type of power supply of the vehicle: diesel, petrol, and electric [39]. The emissions produced by the towing vehicle depend on the aircraft to be towed, (e.g., narrow or wide body) and its fuel (diesel or petrol); Table 2 lists the towing vehicle performance according to the international literature [40,41].

Table 2. Towing vehicle performance.

Aircraft Class	Fuel Type—Energy	Power bhp	Load Factor %	Fuel Consumption gal/bhp-h	HC Emissions g/bhp-h	CO Emissions g/bhp-h	NO_X Emissions g/bhp-h	PM Emissions g/bhp-h	CO_2 Emissions g/gal
Narrow Body	Diesel	175	80	0.061	1.2	4	11	0.55	9797.2
	Petrol	130	80	0.089	4	240	4	0.03	8932.8
	Electric	—	80	—	—	—	—	—	—
Wide Body	Diesel	500	80	0.053	1.2	4	11	0.53	9797.2
	Petrol	500	80	0.089	4	240	4	0.03	8932.8
	Electric	—	80	—	—	—	—	—	—

At the same time, APU is operated to ensure the power supply of the aircraft when the main engines are turned off. It works at lower operating power, in "No Load" conditions (NL) [42] ACRP Report 64. Table 3 lists the APU-NL performances in terms of fuel flow of the *j*-th aircraft ($FF_{j,APU}$) and emission indices due to NL conditions. It should be noted that [42] does not provide information about PM emissions.

Table 3. APU performance parameters in NL conditions.

Aircraft Class	$FF_{j,APU}$ kg/s	HC Emissions g/kg of Fuel	CO Emissions g/kg of Fuel	NO_X Emissions g/kg of Fuel	PM Emissions g/kg of Fuel	CO_2 Emissions g/kg of Fuel
Narrow Body	0.021	6.53	31.75	5.45	—	3155
Wide Body	0.035	0.87	10.26	7.55	—	3155

Finally, it is necessary to consider that the operational towing determines a reduction in the travel speed on taxiways, causing an increase in taxiing time; in addition, the coupling/detachment time of the aircraft from the towing vehicle cannot be overlooked. For these reasons, a multiplication factor of 2.5 is generally applied to the operating time of the taxiing phases [25]. Therefore, the fuel consumption (FC_{APU}) depends on three items: the aircraft operation during the warm-up/cool-down operations, the towing vehicle operation during taxiing, and APU operation (three addenda in Equation (5), respectively):

$$\begin{aligned} FC_{APU} &= \textstyle\sum_j FC_{j,APU} \\ &= \textstyle\sum_j \left(N_j \cdot FF_{j,APU} \cdot \min\{TIM_j \cdot 2.5\,; 300\}\right) + \left(TIM_j \cdot 2.5 \cdot P \cdot c \cdot LF\right) \\ &+ \left(TIM_j \cdot 2.5 - 300\right) \cdot FF_{j,APU} E_{i,SET} = \textstyle\sum_j EI_{ij} \cdot FC_{j,SET} \end{aligned} \quad (5)$$

where $FC_{j,APU}$ is the fuel consumption of the *j*-th aircraft during taxiing in APU conditions (kg), $FF_{j,APU}$ is the fuel flow that measures the weight flow rate of fuel consumed by each engine of the *j*-th aircraft during taxiing (kg/s) in APU conditions; 2.5 is the corrective factor of TIM_j; 300 is the time (in seconds) required to warm up/cool down the engine; *P* is the towing vehicle power (bhp); *c* is the consumption factor of the towing vehicle (kg/bhp*s) according to Table 2; *LF* is the load factor or the reduction of towing efficiency under maximum load (percentage).

Equation (6) gives the total emission index for the polluting agent i produced by APU conditions ($EI_{i,APU}$)

$$E_{i,APU} = \sum_j EI_{ij,APU} \cdot FC_{j,APU} \quad (6)$$

where $E_{ij,APU}$ (kg/(aircraft*bhp*h)) is the emission index for the pollutant *i* when the *j*-th aircraft operates in APU NL conditions.

2.3.3. Onboard Systems

Onboard systems provide traction parallel to the main one, based on the electrification of the landing gears. In this way, the movement of the aircraft is guaranteed autonomously by keeping the main engines off, except for the heating/cooling time. According to [42], APU works at its highest operating power (main engine start, MES). Table 4 lists the APU-

MES performances in terms of fuel flow of the *j*-th aircraft ($FF_{j,MES}$) and emission indices due to MES conditions.

Table 4. APU performance parameters in MES conditions.

Aircraft Class	$FF_{j,MES}$ kg/s	HC Emissions g/kg of Fuel	CO Emissions g/kg of Fuel	NO_X Emissions g/kg of Fuel	PM Emissions g/kg of Fuel	CO_2 Emissions G/Kg of Fuel
Narrow Body	0.038	0.29	4.94	7.64	—	3155
Wide Body	0.064	0.13	0.98	11.53	—	3155

Onboard systems allow aircraft to maintain taxiing speeds unchanged, reaching values comparable to those of taxiing with the engines running. In any case, in this study, it is considered convenient to make a precautionary estimate of a 30% increase in taxiing time. In MES conditions two items contribute to emissions in the taxiing phases with onboard systems: the first one refers to the emissions produced by the aircraft during a 5-min-long warm-up/cool-down, and the second one gives the emissions produced by APU. Equation (7) gives the fuel consumption due to MES conditions (FC_{MES}):

$$FC_{MES} = \sum_j FC_{j,MES} = \sum_j \left[\left(N_j \cdot FF_{j,MES} \cdot 300 \right) + \left(TIM_j \cdot 1.3 \right) \cdot FF_{j,MES} \right] \quad (7)$$

where $FC_{j,MES}$ is the fuel consumption of the *j*-th aircraft during taxiing in MES conditions (kg); $FF_{j,MES}$ is the fuel flow that measures the weight flow rate of fuel consumed by each engine of the *j*-th aircraft during taxiing (kg/s) in MES conditions.

Equation (8) gives the total emission index for the polluting agent *i* produced by MES conditions ($E_{i,MES}$):

$$E_{i,MES} = \sum_j EI_{ij,MES} \cdot \ FC_{j,MES} \quad (8)$$

where $E_{ij,MES}$ (kg/aircraft or #/aircraft) is the emission index for the pollutant *i* when the *j*-th aircraft operates in APU MES conditions.

2.3.4. Reducing Taxiing Time

As a final solution to optimize aircraft taxiing, potential benefits that can be obtained with more accurate management of ground traffic at the airport are evaluated, while maintaining taxiing in FET (RED). Collected data about taxiing time are concentrated in 3 min with respect to the average value. It is therefore considered admissible to consider calculation scenarios with a reduction in taxiing time of 1, 2, and 3 min (RED1, RED2, RED3, respectively), compared to the average values defined in Table 1, as these timeframes frequently occur in real operational scenarios [43]. For the Study Airport, a fast time simulation with runway capacity analyzer and airside capacity analyzer allowed modeling future operative scenarios with optimized ground handling procedures and modified layout of aprons and taxiways [44–46]. In particular, the conflict resolution of taxiing paths and the reduction of the departure queue at runway entry points significantly reduce TIM and emissions [47,48]. The future scenarios allow reduction in taxiing time of 1, 2, and 3 min compared to the current scenario. These values are a characteristic of the aerodrome of study, but the approach can be generalized to other airports.

Therefore, the calculation of fuel consumption (FC_{RED}) and pollutant emissions ($EI_{i,RED}$) during SET taxiing conditions was performed according to Equations (9) and (10)

$$FC_{RED} = \sum_j FC_{j,RED} = \sum_j TIM_j \cdot FF_j \cdot N_j \quad (9)$$

where $FC_{j,RED}$ is the fuel consumption of the *j*-th aircraft during taxiing in FET conditions.

$$E_{i,RED} = \sum_j EI_{ij,RED} \cdot \ FC_{j,RED} \quad (10)$$

where $E_{ij,RED}$ (kg/aircraft or #/aircraft) is the total emissions of the pollutant *i* produced by the *j*-the aircraft during one RED LTO cycle.

2.4. Costs

The definition of strategic choice must necessarily include the calculation of the costs associated with the purchase and fuel consumption in each alternative analyzed in the study. It will thus be possible to quantify the economic savings from each solution, compared to the basic scenario, and steer traffic planners towards the most technically sound and profitable strategy. The analyzed scenarios have been compared to the basic one in terms of total fuel costs (*TC*) (Equation (11)):

$$TC = FC \times unit\ fuel\ price \tag{11}$$

where *FC* refers to the FC values obtained from Equations (1), (3), (5), (7) and (9).

It is emphasized that the aircraft and APU are powered by kerosene combustion, while the towing vehicle is characterized by a different power supply depending on the scenario considered (diesel, petrol, or electric).

The unit kerosene price is obtained through the public analysis provided by the International Air Transport Association (IATA) [49], while the prices of diesel and gasoline are obtained from the Italian Ministry of Economic Development [50]; on the other hand, the cost of electricity for recharging a towing vehicle battery has been overlooked.

2.5. Case Study

The Study Airport is a medium-sized Italian infrastructure, with a single 2800 m long runway, a parallel taxiway, 6 runway exit taxiways, and an apron connected to the parallel taxiway through ten taxiways (Figure 1).

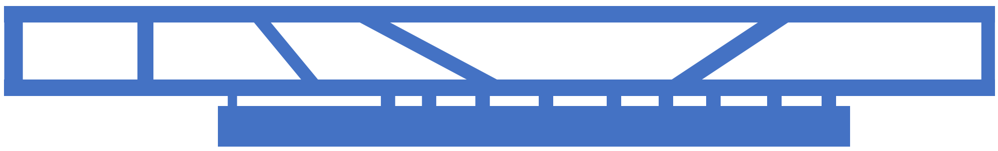

Figure 1. Airport layout.

The airport is in a highly anthropized area: the effort for the local reduction of emissions is strategic. It has traffic of about 70,000 movements/year (take-offs and landings) consisting of the aircraft types listed in Table 5 where the number of LTO cycles and the type and number of engines for each aircraft are also listed.

Table 5. Yearly average traffic mix.

Aircraft Type	Engine Type	Number of Engines	LTO Cycles	Aircraft Type	Engine Type	Number of Engines	LTO Cycles
A30B	PW4158	2	9	CRJ7	GE CF34-8C5	2	39
A310	GE CF6-80C2A2	2	3	CRJ9	GE CF34-8C5	2	2676
A318	CFMI CFM56-5B9/3	2	1069	D328	PW306B	2	12
A319	CFMI CFM56-5B5/P	2	1659	DC8	CFMI CFM56-2C1	2	1
A320	CFMI CFM56-5B4/3	2	4310	DH8C	PWC PW123	2	162
A321	IAE V2533-A5	2	346	DH8D	PWC PW150A	2	466
A330-200	RR Trent 772B-60	2	74	E135	AN AE3007A1	2	654
A330-300	RR Trent 772B-60	2	1	E145	AN AE3007A1	2	37
AN26	Ivchenko AI 24VT	2	135	E170	GE CF34-8E5A1	2	111
AT45	PWC PW127	2	315	E190	GE CF34-10E5A1	2	1102

Table 5. *Cont.*

Aircraft Type	Engine Type	Number of Engines	LTO Cycles	Aircraft Type	Engine Type	Number of Engines	LTO Cycles
AT72	PWC PW120	2	973	F100	RR Tay Mk650-15	2	260
B190	P&W PT6A-65B	2	1	F50	PWC PW125B	2	3
B350	SHP P&W PT6A-60A	2	1	F70	RR Tay Mk650-15	2	1144
B461	ALF502R-5	4	9	GL5T	RR BR710A2-20	2	12
B462	ALF 502R-5	4	322	GLEX	R-R BR710-48-C2	2	16
B463	ALF 502R-5	4	770	J328	P&W 306B	2	11
B737-200	P&W JT8D-9A	2	129	L188	Allison T56-A14	4	1
B737-300	P&W JT8D-9A	2	1166	MD80	PW JT8D-217C	2	2
B737-400	P&W JT8D-9A	2	1822	MD82	PW JT8D-217C	2	1617
B737-500	P&W JT8D-9A	2	538	MD83	PW JT8D-217C	2	74
B737-600	CFMI CFM56-7B20	2	72	MD87	PW JT8D-217C	2	14
B737-700	CFMI CFM56-7B22	2	93	MD90	IAE V2525-D5	2	2
B737-800	CFMI CFM56-7B26	2	6859	RJ1H	LY LF507-1F	4	150
B747-200	PW JT9D-7Q	4	4	RJ70	LY LF 507-1F	4	2
B747-400	GE CF6-80C2B1F	4	3	RJ85	LY LF507-1F	4	514
B757-200	RR RB211-535 E4	2	459	SB20	AN AE2100A	2	144
B767-200	GE CF6-80A2	2	267	SF34	GE CT7-5A2	2	4
B767-300	PW4060	2	140	SH36	P&W PT6A-67R	2	1
CRJ1	GE CF34-3A1	2	2	SW3	Garrett TPE331-10U-503G	2	3
CRJ2	GE CF34-3A1	2	1019	SW4	Garrett TPE331-12	2	9

3. Results

3.1. Pollutant Emissions in the Basic Scenario

Fuel consumption and pollutant emissions in the basic scenario (FET) have been estimated according to Equations (1) and (2) having regard to traffic data in Table 5. Table 6 lists the results.

Table 6. Emissions of FET.

Phase	TIM	Thrust	HC	CO	NO_X	SO_X	PM	CO_2	Fuel
Approach	4.0	30	0.8	9.7	39.8	4.3	0.5	13,416	4252
Taxi-in	6.3	7	5.7	58.9	11.2	2.6	0.2	8205	2601
Taxi-out	12.6	7	11.4	118.7	22.6	5.2	0.5	16,537	5242
Take off	0.7	100	0.3	1.6	63.0	2.6	0.4	8228	2608
Climb out	2.2	85	0.8	4.1	130.5	6.7	1.0	21,281	6745
LTO cycle	25.8	—	19.0	193.1	267.0	21.4	2.6	67,668	21,448

Each pollutant quantity depends on the TIM of each phase of the LTO cycle and the percentage of thrust operated by the aircraft engines. HC and CO appear to be mainly produced during the incomplete combustion process, associated with the operation of engines at low operating thrusts. Therefore, the results show that over 90% of HC and CO are associated with taxiing phases that are characterized by longer operating time and by the lowest exploitation of the aircraft engines (7%). On the other hand, the fuel consumption and the production of the other polluting species (NO_X, PM, SO_X, and CO_2) are proportional to the high operating thrusts. Therefore, the highest concentration and production values are expected in the take-off phases (thrust 100%) and climb out (thrust 85%). Moreover, the results show a strong incidence of TIM: the greatest concentration is associated with the climb-out phase, while the contributions obtained in the taxiing phases are also relevant, affected by long operational time.

3.2. Pollutant Emissions According to the Optimization Scenarios

Table 7 lists the results obtained with the alternative taxiing modes, (i.e., SET, APU-NL, APU-MES; RED) described in Section 2. For each proposed scenario, the values of the air emissions and the fuel consumption are compared with those of FET one (values in Table 6). Only the results obtained for the taxiing phases and the effects induced on the complete LTO cycle are reported because no operational modification is considered for the other phases.

Table 7. Airport emission scenarios.

Taxiing Mode	Phase	HC Ton	CO Ton	NO_X Ton	SO_X Ton	PM Ton	CO_2 Ton	Fuel Consumption Ton
SET	Taxi-in	5.1 −10.1%	53.0 −10.1%	10.1 −10.1%	2.3 −10.1%	0.2 −10.1%	7379 −10.1%	2339 −10.1%
	Taxi-out	8.0 −30.2%	82.9 −30.2%	15.8 −30.2%	3.7 −30.2%	0.3 −30.2%	11544 −30.2%	3659 −30.2%
	LTO-cycle	15.0 −21.2%	151.3 −21.6%	259.0 −3.0%	19.6 −8.6%	2.4 −6.5%	61,849 −8.6%	19,603 −8.6%
RED1	Taxi-in	4.8 −16.0%	49.5 −16.0%	9.4 −16.0%	2.2 −16.0%	0.2 −16.0%	6895 −16.0%	2185 −16.0%
	Taxi-out	10.5 −7.9%	109.3 −7.9%	20.8 −7.9%	4.8 −7.9%	0.4 −7.9%	15,227 −7.9%	4826 −7.9%
	LTO-cycle	17.2 −9.5%	174.3 −9.8%	263.4 −1.3%	20.6 −3.9%	2.5 −2.9%	65,047 −3.9%	20,617 −3.9%
RED2	Taxi-in	3.9 −31.9%	40.1 −31.9%	7.6 −31.9%	1.8 −31.9%	0.2 −31.9%	5585 −31.9%	1770 −31.9%
	Taxi-out	9.6 −15.8%	99.9 −15.8%	19.0 −15.8%	4.4 −15.8%	0.4 −15.8%	13,916 −15.8%	4411 −15.8%
	LTO-cycle	15.4 −19.1%	155.4 −19.5%	259.8 −2.7%	19.8 −7.8%	2.4 −5.9%	62,427 −7.8%	19,787 −7.8%
RED3	Taxi-in	3.0 −47.9%	30.7 −47.9%	5.8 −47.9%	1.4 −47.9%	0.1 −47.9%	4274 −47.9%	1355 −47.9%
	Taxi-out	8.7 −23.8%	90.5 −23.8%	17.2 −23.8%	4.0 −23.8%	0.4 −23.8%	12,606 −23.8%	3996 −23.8%
	LTO-cycle	13.6 −28.6%	136.6 −29.2%	256.2 −4.0%	19.0 −11.6%	2.3 −8.8%	59,806 −11.6%	18,956 −11.6%
APU diesel	Taxi-in	8.4 48.5%	64.0 8.6%	23.4 109.0%	2.7 3.4%	0.8 240.1%	8481 3.4%	2478 −4.7%
	Taxi-out	13.6 19.0%	87.2 −26.6%	39.2 73.4%	2.9 −33.2%	1.4 199.8%	11,043 −33.2%	3077 −41.3%
	LTO-cycle	23.9 25.9%	166.6 −13.7%	295.8 10.8%	19.2 −7.7%	4.1 59.3%	62,449 −7.7%	19,161 −7.7%
APU petrol	Taxi-in	10.5 84.3%	261.5 343.8%	14.5 29.6%	2.7 3.4%	0.2 −9.4%	8488 3.4%	2478 −4.7%
	Taxi-out	17.7 54.7%	485.2 308.6%	21.2 −5.9%	3.5 −33.1%	0.2 −49.6%	1105 −33.1%	3077 −41.3%
	LTO-cycle	30.0 58.1%	762.0 294.7%	269.0 0.7%	19.8 −7.7%	2.3 −10.1%	62,470 −7.7%	19,161 −7.7%
APU electric	Taxi-in	7.1 25.0%	59.5 1.1%	11.2 −0.4%	2.5 −4.7%	0.2 −20.2%	7819 −4.7%	2478 −4.7%
	Taxi-out	10.9 −4.6%	78.2 −34.1%	14.5 −36.0%	3.1 −41.3%	0.2 −60.4%	9709 −41.3%	3077 −41.3%
	LTO-cycle	19.9 4.7%	153.2 −20.7%	258.8 −3.1%	18.6 −10.7%	2.2 −13.1%	60,453 −10.7%	19,161 −10.7%
MES	Taxi-in	4.7 −17.4%	49.7 −15.6%	13.3 18.3%	2.6 1.2%	0.2 −20.2%	8304 1.2%	2632 1.2%
	Taxi-out	4.8 −57.6%	52.4 −55.8%	17.6 −22.0%	3.2 −39.0%	0.2 −60.4%	10,083 −39.0%	3196 −39.0%
	LTO-cycle	11.4 −39.8%	117.6 −39.1%	264.1 −1.1%	19.4 −9.4%	2.2 −13.1%	61,313 −9.4%	19,434 −9.4%

In the taxi-in phase, significant reductions in all pollutant emissions are achieved by applying SET (−10.1%) and ensuring better management of the surface traffic (−16.0%, −31.9%, −47.9% for RED1, RED2, and RED3, respectively). Such strategies reduce in equal percentages all the pollutants since the taxi operating time of aircraft engines is reduced. Dispatch towing with internal combustion vehicles (diesel/petrol) implies a generalized increase in the pollutant concentrations due to the emission package of the towing vehicle and APU; more specifically, a diesel-powered towing vehicle causes an increase in NO_X equal to 109% and PM equal to 240%, while a petrol-fuelled towing vehicle generates an increase in CO of up to 344%. Electric towing vehicles, on the other hand, provide a less unfavorable scenario, with a 25% increase in HC. The onboard systems (MES mode) determine a good reduction of pollutants (except for an 18.3% increase in NO_X), but due to the operating APU, there is a minimal increase in fuel consumption (1.2%).

The taxi-out phase implies a longer operating time than taxi-in: this condition causes a greater impact on the containment of emissions when the aircraft's main engines are kept off because the fuel consumption is significantly reduced. In the taxi-out phase, SET conditions ensure a significant reduction in the emissions (−30.2%) and interesting results are from the improvement of ground operations (−7.9%, −15.8%, −23.8% for RED1, RED2, and RED3, respectively. Onboard systems are a valid option: the fuel consumption is reduced by 39.0%: it generates −57.6% for HC and −60.4% for PM. Even the electric-powered towing system can be considered a favorable scenario since gives slightly to the maximum reduction in fuel consumption (−41.3%): in any case, the operational consequences, (i.e., the increase in taxiing time) do not make this solution advantageous to justify its application. Finally, the towing solutions with internal combustion vehicles (diesel/petrol) also for the taxi-out define emission scenarios not compliant with the mitigation objective: diesel towing determines an increase in PM equal to 199.8% and NO_X equal to 73.4%; petrol-fuelled towing generates an increase in CO equal to 308.6%.

3.3. Cost Analysis

Table 8 lists the results obtained in terms of yearly fuel costs in the examined taxiing modes.

Table 8. Yearly fuel costs for different scenarios.

Mode	Kerosene (€)	Diesel/Petrol (€)	Total (€)	Difference with Respect to FET (€)
FET	11,825,396	0	11,825,396	-
SET	10,808,411	0	10,808,411	−1,016,985
RED1	11,367,408	0	11,367,408	−457,988
RED2	10,909,420	0	10,909,420	−915,976
RED3	10,451,432	0	10,451,432	−1,373,963
APU diesel	10,564,583	1,236,851	11,801,434	−23,961
APU petrol	10,564,583	1,460,274	12,024,857	199,461
APU electric	10,564,583	0	10,564,583	−1,260,813
MES	10,714,738	0	10,714,738	−1,110,658

The graph shows the greatest savings can be achieved with the correct optimization of the surface handling operations inside the airport, both at entry and exit. Towing scenarios with electric vehicles and onboard systems ensure comparable savings results. On the other hand, the petrol trailer scenario defines overall costs as higher than FET.

Figure 2 represents for each taxi mode the fuel cost (blue bars) and the difference with respect to the FET scenario: savings are represented with green bars, while the red bar shows the additional cost value.

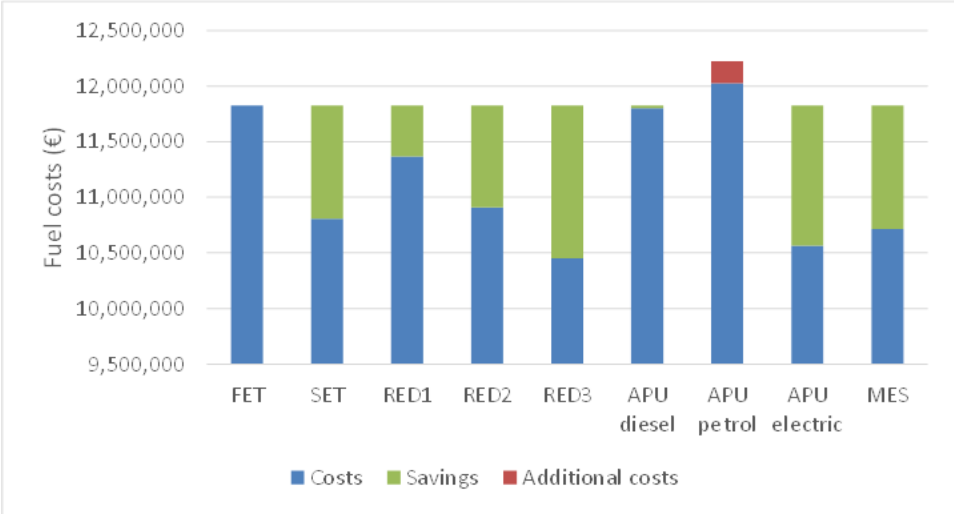

Figure 2. Costs comparison.

4. Discussion

The results can be interpreted also in terms of different time horizons: short and long terms compared to the current FET mode. The former, immediately implementable, is at virtually no cost; the latter calls for targeted investment and development plans.

In the short term, with no changes to the airport infrastructure and without significant economic investment, neither by the airport management nor by the airlines, the best solution in terms of fuel consumption is SET both in the taxi-in (−10.1%) and taxi-out (−30.2%) phases. This strategy allows reducing in the LTO cycle the fuel consumption by −8.6%, and the pollutant emissions between −3.0% for NO_X and −21.6% for CO (Table 9).

Table 9. Results of SET conditions in the short-term scenario.

Phase	HC Ton	CO Ton	NO_X Ton	SO_X Ton	PM Ton	CO_2 Ton	Fuel Consumption Ton
Approach	0.8 0%	9.7 0%	39.8 0%	4.3 0%	0.5 0%	13,416 0%	4252 0%
Taxi-in (SET)	5.1 −10.1%	53.0 −10.1%	10.1 −10.1%	2.3 −10.1%	0.2 −10.1%	7379 −10.1%	2339 −10.1%
Taxi-out (SET)	8.0 −30.2%	82.9 −30.2%	15.8 −30.2%	3.7 −30.2%	0.3 −30.2%	11,544 −30.2%	3659 −30.2%
Take off	0.3 0%	1.6 0%	63.0 0%	2.6 0%	0.4 0%	8228 0%	2608 0%
Climb out	0.8 0%	4.1 0%	130.5 0%	6.7 0%	1.0 0%	21,281 0%	6745 0%
LTO cycle	15.0 −21.2%	151.3 −21.6%	259.0 −3.0%	19.6 −8.6%	2.4 −6.5%	61,849 −8.6%	19,603 −8.6%

SET in the short period ensures a saving related to the fuel purchase of 1,016,985 €/year (Table 8). Such value should be divided into −144,489 €/year and −872,496 €/year in the taxi-in and taxi-out phases, respectively.

For the long-term scenario (Table 10), the airport's specific development plans to upgrade the infrastructure or improvements to increase the sustainability of the fleet can be considered. It is considered convenient to aim for at least a 2-min reduction in the taxi-in time (RED2) because it implies a reduction in emissions equal to −31.9%). In turn, for the taxi-out phase, the scenario that can be obtained with onboard systems (MES) is optimal, guaranteeing conspicuous reductions of pollutants (between −22% for NO_x and −60.4% of PM) and fuel consumption (−39.0%).

Table 10. Results of SET conditions in the long-term scenario.

Phase	HC Ton	CO Ton	NO_X Ton	SO_X Ton	PM Ton	CO_2 Ton	Fuel Consumption Ton
Approach	0.8 0%	9.7 0%	39.8 0%	4.3 0%	0.5 0%	13,416 0%	4252 0%
Taxi-in (RED2)	3.9 −31.9%	40.1 −31.9%	7.6 −31.9%	1.8 −31.9%	0.2 −31.9%	5585 −31.9%	1770 −31.9%
Taxi-out (MES)	4.8 −57.6%	52.4 −55.8%	17.6 −22.0%	3.2 −39.0%	0.2 −60.4%	10,083 −39.0%	3196 −39.0%
Take off	0.3 0%	1.6 0%	63.0 0%	2.6 0%	0.4 0%	8228 0%	2608 0%
Climb out	0.8 0%	4.1 0%	130.5 0%	6.7 0%	1.0 0%	21,281 0%	6745 0%
LTO cycle	10.6 −44.2%	108.0 −44.1%	258.4 −3.2%	18.6 −13.4%	2.2 −14.2%	58,593 13.4%	18,572 −13.4%

On the whole, the best options for taxi-in and taxi-out ensure a significant reduction in fuel consumption compared to the current FET mode (−13.4%) and imply interesting results in terms of reduced HC and CO emissions (−44%).

The long-term scenario enables a saving of −457,988 €/year for the taxi-in (RED2 mode) and −1,127,879 €/year for the taxi-out (MES mode). The overall cost reduction is −1,585,867 €/year, 56% more than the short-term scenario.

However, the implications of finding low-impact solutions go beyond the simple quantification of saving fuel and reducing emissions. The study will continue in this analysis and will address the comparison of the magnitude of the pollution emissions generated by ground operations, according to the adopted methodology, with those generated by other sources such as road traffic attracted and generated by the airport [51]. Proper knowledge of the magnitude of both will also help the accuracy of tools such as environmental and strategic impact studies on airport areas and other urban mobility plans and airport masterplans.

5. Concluding Remarks

This study determined the emission scenarios produced by aircraft within an Italian airport. It analyzed four different alternative measures for ground handling, to establish a strategic solution that ensures the lowest environmental impact for the facility and the surrounding areas, based on technical and economic considerations. Four different taxiing modes, (i.e., single-engine taxiing, dispatch towing, taxing with onboard systems, and reducing taxiing time) were studied and compared to the current operational scenario. The analysis focused on the emissions from fuel combustion and the fuel costs: HC, CO, CO_2, NO_X, SO_X, and PM have been assessed according to international approaches provided by ICAO. Two different horizons have been considered to identify the best strategy during the service life of the airport: short-term is promptly at virtually no cost, while long-term needs for targeted investment and development plans of the infrastructure. In the short term, single-engine taxiing is the best solution both in the taxi-in and taxi-out phases of the LTO cycle: the overall reduction in emissions ranges between 3 and 21%, and fuel consumption is reduced by 8.6%. In the long-term, the reduction of the 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 the taxiing with onboard systems result in the best solution (up to −57.6% for HC).

One very last point to consider is that the results from the emissions scenarios might call for some caveats. Firstly, they are test results from the specific case study in hand, and further studies to consolidate these findings are currently in progress to this end, analyzing operations on the busiest airport with severer environmental problems [51]. Very preliminary results are promising, which might seem to indicate that the presented strategies would be generally feasible. At the same time, this shifts the focus on uncertainty in terms of operational policies. The scenarios and results presented to be widely implemented require the full acceptance of airline carriers, which usually tend to match operational efficiency with environmental friendliness. As demonstrated, the reduced fuel consumption should be a driver, representing a not negligible saving item, but certainly, to consolidate as a practice and provide long-term benefits, the proposed taxiing strategies are to be framed within specific regulatory tools (air traffic plans, sustainable urban mobility plans, air quality plans, etc.), to become structural. This might involve the consensus also from ground operators and traffic controllers, along with the airlines and the progress of transport policies in this direction.

Author Contributions: Conceptualization, P.D.M.; data curation, L.M.; formal analysis, N.R.R.; investigation, M.V.C. and L.M.; methodology, P.D.M. and L.M.; validation, P.D.M. and M.V.C.; writing—original draft, P.D.M., M.V.C. and L.M.; writing—review and editing, M.V.C. and L.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: Not applicable.

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

References

1. IATA. The IATA Technology Roadmap Report. 2009. Available online: https://www.escholar.manchester.ac.uk/api/datastream?publicationPid=uk-ac-man-scw:106699&datastreamId=FULL-TEXT.PDF (accessed on 28 June 2022).
2. European Commission. Reducing Emissions from Aviation. 2017. Available online: https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-aviation_en (accessed on 5 July 2022).
3. International Civil Aviation Organization (ICAO). Trends in Emissions that Affect Climate Change. Available online: https://www.icao.int/environmental-protection/Pages/ClimateChange_Trends.aspx (accessed on 13 July 2022).
4. Eyring, V.; Kohler, H.W.; Lauer, A.; Lemper, B. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. *J. Geophys. Res. Atmos.* **2005**, *110*, D17306. [CrossRef]
5. Vennam, L.P.; Vizuete, W.; Talgo, K.; Omary, M.; Binkowski, F.S.; Xing, J.; Mathur, R.; Arunachalam, S. Modeled Full-Flight Aircraft Emissions Impacts on Air Quality and Their Sensitivity to Grid Resolution. *J. Geophys. Res. Atmos.* **2017**, *122*, 13472–13494. [CrossRef] [PubMed]
6. Riley, K.; Cook, R.; Carr, E.; Manning, B. A systematic review of the impact of commercial aircraft activity on air quality near airports. *City Environ. Interact.* **2021**, *11*, 100066. [CrossRef]
7. Hudda, N.; Durant, L.W.; Fruin, S.A.; Durant, J.L. Impacts of Aviation Emissions on Near-Airport Residential Air Quality. *Environ. Sci. Technol.* **2020**, *54*, 8580–8588. [CrossRef] [PubMed]
8. Bendtsen, K.M.; Bengtsen, E.; Saber, A.T.; Vogel, U. A review of health effects associated with exposure to jet engine emissions in and around airports. *Environ. Health* **2021**, *20*, 10. [CrossRef]
9. Klöwer, M.; Allen, M.R.; Lee, D.S.; Proud, S.R.; Gallagher, L.; Skowron, A. Quantifying aviation's contribution to global warming. *Environ. Res. Lett.* **2021**, *16*, 104027. [CrossRef]
10. Wells, C.A.; Williams, P.D.; Nichols, N.K.; Kalise, D.; Poll, I. Reducing transatlantic flight emissions by fuel-optimised routing. *Environ. Res. Lett.* **2021**, *16*, 025002. [CrossRef]
11. International Civil Aviation Organization (ICAO). Document 9889. Airport Air Quality Manual, Second Edition. Available online: https://www.icao.int/publications/Documents/9889_cons_en.pdf (accessed on 2 July 2022).
12. Celikel, A.; Duhanian, N.; Peeters, S. *Preliminary Local Air-Quality Study*; Report EEC/BA/ENV/Note No. 001/2002; Environmental Studies Business Area, EUROCONTROL Experimental Centre: Brussels, Belgium, 2002.
13. European Union Aviation Safety Agency (EASA). European Aviation Environmental Report, Chapter 7. Available online: https://www.easa.europa.eu/eaer/topics/aviation-environmental-impacts (accessed on 1 July 2022).

14. European Union Aviation Safety Agency (EASA). Agency Research Agenda 2020–2022. Available online: https://www.easa.europa.eu/downloads/117222/en (accessed on 1 July 2022).
15. Postorino, M.N. Environmental effects of airport nodes: A methodological approach. *Int. J. Sustain. Dev. Plan.* **2010**, *5*, 192–204. [CrossRef]
16. 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. [CrossRef]
17. Brennan, E. EUROCONTROL 2050 air traffic forecast and Objective Skygreen provide guidance for a purposeful long-term aviation sustainability. In *EUROCONTROL Aviation Sustainability Briefing*; EUROCONTROL: Brussels, Belgium, 2022; Volume 6, pp. 2–3.
18. EUROCONTROL Objective Skygreen 2022–2030. The Economics of Aviation Decarbonisation towards the 2030 Green Deal Milestone. 2022. Available online: https://www.eurocontrol.int/sites/default/files/2022-05/eurocontrol-objective-skygreen-2022-2030-report-20220523.pdf (accessed on 1 July 2022).
19. European Union Aviation Safety Agency (EASA). Sustainable Aviation Fuel 'Monitoring System. Available online: https://www.easa.europa.eu/downloads/115346/en (accessed on 1 July 2022).
20. Fan, W.; Sun, Y.; Zhu, T.; Wen, Y. Emissions of HC, CO, NO_X, CO_2 and SO_2 from civil aviation in China in 2010. *Atmos. Environ.* **2012**, *56*, 52–57. [CrossRef]
21. Stettler, M.E.J.; Eastham, S.; Barret, S.R.H. Air Quality and public health impacts of UK airports. Part I: Emissions. *Atmos. Environ.* **2011**, *45*, 5415–5424. [CrossRef]
22. Yim, S.H.L.; Stettler, M.E.J.; Barret, S.R.H. Air Quality and public health impacts of UK airports. Part II: Impacts and policy assessment. *Atmos. Environ.* **2013**, *67*, 5415–5424. [CrossRef]
23. 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. [CrossRef]
24. Tait, K.N.; Khan, M.A.H.; Bullock, S.; Lowenberg, M.H.; Shallcross, D.E. Aircraft Emissions, Their Plume-Scale Effects, and the Spatio-Temporal Sensitivity of the Atmospheric Response: A Review. *Aerospace* **2022**, *9*, 355. [CrossRef]
25. Balakrishnan, H.; Deonandan, I.; Simaiakis, I. *Opportunities for Reducing Surface Emissions through Airport Surface Movement Optimization*; Technical Report ICAT 2008/7; MIT International Center for Air Transportation: Cambridge, MA, USA, 2008; Available online: http://hdl.handle.net/1721.1/66491 (accessed on 1 July 2022).
26. Miller, B.; Minoque, K.; Clarke, J. *Constraints in Aviation Infrastructure and Surface Aircraft Emissions*; Massachusetts Institute of Technology: Cambridge, MA, USA, 2000; pp. 1–15.
27. Di Mascio, P.; Carrara, R.; Frasacco, L.; Luciano, E.; Ponziani, A.; Moretti, L. Influence of tower air traffic controller workload and airport layout on airport capacity. *J. Airpt. Manag.* **2021**, *15*, 408–423.
28. Guo, R.; Zhang, Y.; Wang, Q. Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. *Transp. Res. C* **2014**, *44*, 98–109. [CrossRef]
29. Li, J.; Yang, H.; Liu, X.; Yu, N.; Tian, Y.; Zhou, X.; Zhang, P.; Wang, K. Aircraft Emission Inventory and Characteristics of the Airport Cluster in the Guangdong–Hong Kong–Macao Greater Bay Area, China. *Atmosphere* **2020**, *11*, 323. [CrossRef]
30. International Civil Aviation Organization (ICAO). Manual of the ICAO Standard Atmosphere—3rd Edition 1993 (Doc. 7488). DOC-07488-003-01-Q-P. Available online: http://www.aviationchief.com/uploads/9/2/0/9/92098238/icao_doc_7488_-_manual_of_icao_standard_atmosphere_-_3rd_edition_-_1994.pdf (accessed on 5 July 2022).
31. Ivković, I.; Čokorilo, O.; Kaplanović, S. The estimation of GHG emission costs in road and air transport sector: Case study of Serbia. *Transport* **2018**, *33*, 260–267. [CrossRef]
32. Du Bois, D.; Paynter, G.C. Fuel flow method 2 for estimating aircraft emissions. *SAE Trans.* **2006**, *115*, 1–14.
33. Mazaheri, M.; Johnson, G.R.; Morawska, L. Particle and Gaseous Emissions from Commercial Aircraft at Each Stage of the Landing and Takeoff Cycle. *Environ. Sci. Technol.* **2009**, *43*, 441–446. [CrossRef]
34. Chati, S.Y.; Balakrishnan, H. Analysis of aircraft fuel burn and emissions in the landing and take-off cycle using operational data. In Proceedings of the International Conference on Research in Air Transportation, Istanbul, Turkey, 26–30 May 2014.
35. International Civil Aviation Organization (ICAO). Aircraft Engine Emission Data Bank (07/2021). Available online: https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank (accessed on 2 June 2022).
36. Wilkerson, J.T.; Jacobson, M.Z.; Malwitz, A.; Balasubramanian, S.; Wayson, R.; Fleming, G.; Naiman, A.D.; Lele, S. Analysis of emission data from global commercial aviation: 2004 and 2006. *Atmos. Chem. Phys.* **2010**, *10*, 6391–6408. [CrossRef]
37. Wasiuk, D.K.; Lowenberg, M.H.; Shallcross, D.E. An aircraft performance model implementation for the estimation of global and regional commercial aviation fuel burn and emissions. *Transp. Res. D* **2015**, *35*, 142–159. [CrossRef]
38. Koudis, G.S.; Hu, S.J.; Majumdar, A.; Ochieng, W.Y.; Settler, M.E.J. The impact of single engine taxiing on aircraft fuel consumption and pollutant emissions. *Aeronaut. J.* **2018**, *122*, 1967–1984. [CrossRef]
39. Lukic, M.; Hebala, A.; Giangrande, P.; Klumpner, C.; Nuzzo, S.; Chen, G.; Gerada, C.; Eastwick, C.; Galea, M. State of the art of electric taxiing systems. In Proceedings of the IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles International Transportation Electrification Conference (ESARS-ITEC), Nottingham, UK, 7–9 November 2018; pp. 1–6.
40. Environmental Protection Agency (EPA). *Technical Support for Development of Airport Ground Support Equipment Emission Reductions*; Environmental Protection Agency: Washington, DC, USA, 1999.

41. California Air Resources Board (CARB). *Air Pollution Mitigation Measures for Airports and Associated Activity*; National Technical Information Service: Springfield, VA, USA, 1994.
42. Airport Cooperative Research Program (ACRP). *Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems*; Report 64; Transportation Research Board: Washington, DC, USA, 2012.
43. Di Mascio, P.; Moretti, L. Hourly Capacity of a Two Crossing Runway Airport. *Infrastructures* **2020**, *5*, 111. [CrossRef]
44. Di Mascio, P.; Cervelli, D.; Comoda Correra, A.; Frasacco, L.; Luciano, E.; Moretti, L.; Nichele, S. A Critical Comparison of Airport Capacity Studies. *J. Airpt. Manag.* **2020**, *21*, 307–321.
45. Di Mascio, P.; Cervelli, D.; Comoda Correra, A.; Frasacco, L.; Luciano, E.; Moretti, L. Effects of Departure manager and arrival manager systems on airport capacity. *J. Airpt. Manag.* **2021**, *15*, 204–218.
46. Di Mascio, P.; Carrara, R.; Frasacco, L.; Luciano, E.; Ponziani, A.; Moretti, L. How the Tower Air Traffic Controller Workload Influences the Capacity in a Complex Three-Runway Airport. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2807. [CrossRef]
47. Čokorilo, O. Human Factor Modelling for Fast-Time Simulations in Aviation. *Aircr. Eng. Aerosp. Technol.* **2013**, *85*, 389–405. [CrossRef]
48. Simaiakis, I.; Balakrishnan, H. Queuing models of airport departure processes for emissions reduction. In Proceedings of the AIAA Guidance, Navigation, and Control Conference, Chicago, IL, USA, 10–13 August 2009.
49. IATA. Jet Fuel Price Monitor. 2021. Available online: https://www.iata.org/en/publications/economics/fuel-monitor/ (accessed on 29 June 2022).
50. Ministero dello Sviluppo Economico. Prezzi Medi Settimanali dei Carburanti e Combustibili. 2021. Available online: https://dgsaie.mise.gov.it/prezzi-settimanali-carburanti (accessed on 14 July 2022).
51. Corazza, M.V.; di Mascio, P.; Esposito, G. Airports as sensitive areas to mitigate air pollution: Evidences from a case study in Rome. *Environments*, 2022; *submitted*.