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Chemical Emissions and Near-Field Dispersion of Suborbital Carriers in Conceptual Design

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Abstract. As suborbital flights and space tourism move from promise to practice, quantifying their near-ground emissions is essential for responsible deployment and regulatory assessment. This study develops a reproducible, end-to-end methodology to quantify propulsive emissions and near-field plume dispersion for a suborbital carrier aircraft. The methodology is demonstrated on a representative point-to-point mission from the Italian Taranto–Grottaglie spaceport, transporting Virgin Galactic's SpaceShipTwo to approximately 15 km prior to release. Objectives are to generate phase-resolved emission source terms and translate them into site-specific ground concentrations to support early design and regulatory assessment. The methodology integrates high-fidelity mission simulations with the analytical BFFM2 emissions-estimation method to compute chemical source terms in an "idle-to-idle" approach, distinguishing fuel-proportional species (CO_2, H_2O, SOx), from power-dependent species (CO, NO_x, HC, PM). For each Landing and Take-Off (LTO) cycle phase, phase-averaged emission rates are represented as continuous elevated point sources and fed into an analytical Gaussian-plume model to compute spatially resolved concentrations C(x,y,z) of pollutants and greenhouse gases. The methodology is benchmarked against airport dispersion measurements and validated by cross-comparison with high-fidelity pollutant dispersion simulations. The proposed framework provides regulators and designers with a validated, transparent tool for early environmental evaluation of reusable suborbital operations, enabling informed decisions on site selection and operational constraints.

Introduction

Suborbital spaceflight is an emerging segment offering promising scientific and commercial opportunities, yet its environmental impacts remain poorly characterized. As air traffic and space tourism grow, rigorous evaluation of propulsive emissions has become critical, specifically for near-ground air-quality assessments [1,2,3,4]. In this regard, the present paper discloses a conceptual design methodology to quantify aircraft emissions and near-field plume dispersion for a suborbital launch system. In a representative point-to-point (A-to-A) mission from the Taranto-Grottaglie Italian spaceport - currently under evaluation by Italian and European authorities as a potential host site for Virgin Galactic's first European suborbital flights [5], chemical emissions from the WhiteKnightTwo (WK2) carrier aircraft are quantified and ground-level pollutant concentrations are estimated during transport of the SpaceShipTwo (SS2) suborbital vehicle to ~15 km altitude before release [6,7]. High-fidelity mission simulations provided time-resolved fuel flow, thrust and atmospheric data, which are combined with ICAO-certified emission indices [8]

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Materials Research Proceedings 69 (2026) 1018-1023 https://doi.org/10.21741/9781644904251-176

to derive fuel-flow-adjusted emission trends at altitude. Specifically, the BFFM2 [9,10] emissions estimation method is adopted to compute chemical emissions in a "idle-to-idle" approach. Then, local air quality impact assessment is carried out. A simplified Gaussian-plume model estimating NO_x dispersion from the aircraft near the runway is implemented [11,12]. The plume model computes the concentration field C(x,y,z) given emission rate Q and local meteorological conditions [13,14,15,16]. Crucially, this implementation is validated against published airport NO_x measurements and dispersion studies, showing reasonable agreement [17]. The presented conceptual design methodology integrates suborbital mission analysis with environmental assessment techniques, constituting a novel contribution to the field.

Methodology

The adopted methodology establishes a coherent and reproducible protocol that integrates high-fidelity mission simulations with analytical models for emissions estimation and atmospheric dispersion, as illustrated in Figure 1. The objective is to characterize the environmental footprint of the WK2 suborbital carrier aircraft during all operational phases.

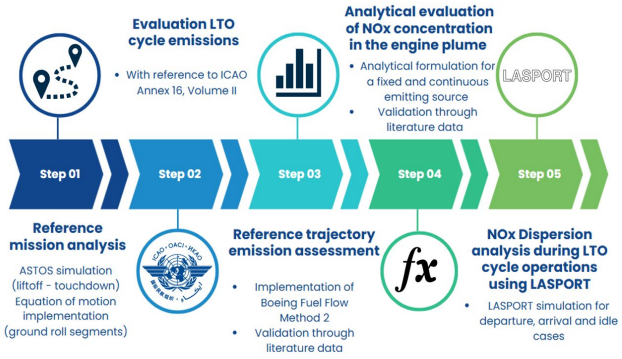


Fig. 1 - Air quality impact assessment methodology

The first step involves the simulation of the reference mission using a high-fidelity trajectory optimization environment. In this case, the authors selected the Analysis, Simulation and Trajectory Optimization Software for Space Applications (ASTOS) [18]. While ASTOS accurately models the airborne phases of flight, it does not explicitly simulate ground operations. To complement this, a dedicated simulation based on the equations of motion and Raymer's semi-empirical formulations was implemented to model the take-off and landing ground rolls, thereby enabling a complete "gate-to-gate" representation of the carrier mission [19]. This approach provides time-resolved outputs of fuel flow, thrust, engine operating conditions, and atmospheric parameters along the overall flight path. These data constitute the dynamic basis for the subsequent emission calculations. Chemical emissions are computed using a dedicated analytical model, namely the Boeing Fuel Flow Method 2 (BFFM2) [10]. This methodology relies on semi-empirical correlations documented in the literature, enabling the estimation of chemical emissions. To derive the Emission Indices (EI) of pollutants and greenhouse gases, expressed as grams of emitted species per kilogram of fuel burned, the BFFM2 procedure is applied as follows: (i) the flight-level fuel flow is corrected to an equivalent sea-level value; (ii) the corrected fuel flow is then used to infer sea-level emission indices through interpolation of tabulated data from the ICAO Engine Emissions Databank [8]; and (iii) the sea-level EIs are subsequently adjusted with altitude-dependent correction factors documented for each chemical species. This procedure yields altitude-corrected emission indices along the entire flight trajectory. For near-field air-quality evaluation, the disclosed methodology employs an analytical Gaussian-plume model to estimate pollutant dispersion and ground-level concentration fields [14,15,16]. Each LTO phase is modeled as a continuous elevated point source emitting a constant phase-averaged mass flow rate Q derived

Materials Research Proceedings 69 (2026) 1018-1023 https://doi.org/10.21741/9781644904251-176

from the emission calculations. The spatio-temporal concentration distribution $C(x, y, z, t)$ at any downwind location is given by the Gaussian-plume simplified formulation reported in Eq.1.

$$C(x,y,z,t) = \frac{Q}{(4\pi t)^{\frac{3}{2}}\sqrt{K_x K_y K_z}} \exp\left(\frac{(x-x')^2}{4K_x t} - \frac{(y-y')^2}{4K_y t} - \frac{(z-z')^2}{4K_z t}\right) \quad (1)$$

Where the K_i are the atmospheric turbulence coefficients calculated from the dispersion parameters obtained using Green's formulations [16]. The atmospheric dispersion model is based on the analytical solution of the advection-diffusion equation under the assumption of constant diffusion coefficients. However, to better reflect atmospheric conditions, the lateral and vertical diffusion parameters were treated as functions of distance, using the Pasquill-Gifford formulations [13]. This approach effectively adapts the Gaussian solution to account for atmospheric turbulence and stability variations. After defining a spatial grid in the vicinity of the emission points representing the LTO cycle phases, it is possible, for each grid node, to (i) calculate the concentration at each time step during the phase, and (ii) determine the mean concentration over the entire phase duration at each grid node. The spatial grid considered is 30 m wide in each direction and centered on the emission source, where the concentration values are the highest. Verification and validation represent the final step of the proposed workflow. Emission and dispersion results are benchmarked against published airport studies and compared with existing assessments of the WK2 aircraft and other large twin-fuselage carriers. Specifically, to validate the concentration results near the spaceport obtained with the simplified Gaussian plume model, high-fidelity dispersion analyses of WK2 NO_x emissions are performed using the commercial software LASPORT [20]. LASPORT represents the standard modeling tool adopted by the German Airport Association and has been applied in several national and international studies (e.g., [21,22]).

Results and Discussion

To address social acceptance concerns among communities surrounding Taranto-Grottaglie Airport, a comparative analysis was performed between the WK2 and the Boeing 747 LCF Dreamlifte, which operates weekly flights from Grottaglie to Charleston to transport fuselage sections of the Boeing 787 Dreamliner. Since LTO emissions and pollutants dispersion are the primary contributors to local air quality impacts, this comparison demonstrates that A-to-A suborbital operations could be integrated into conventional civil aviation without significant effects on nearby populations. Figure 2 compares the total mass of emissions produced by the two aircraft during their LTO cycles.

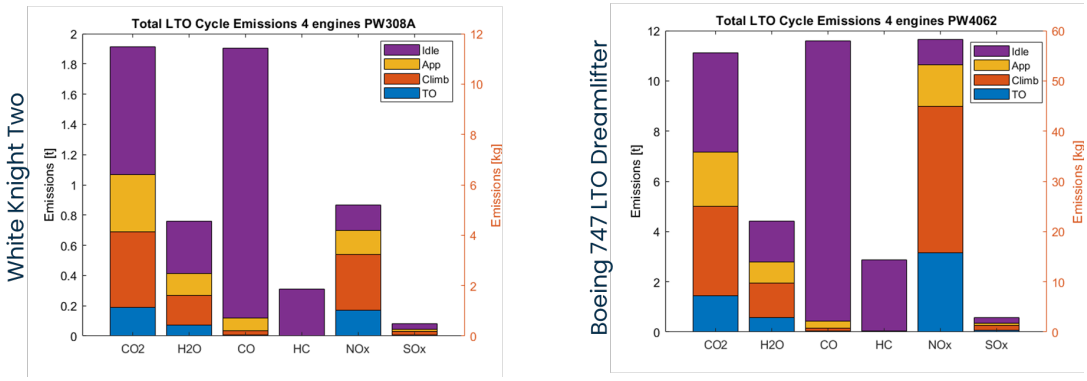
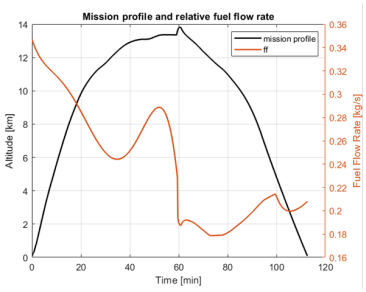


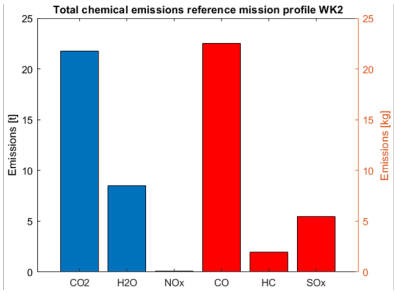
Fig. 2 - Total LTO cycle emissions, WK2 vs Dreamlifter

The Boeing 747 LCF Dreamlifter, equipped with four Pratt & Whitney PW4062 turbofan engines, exhibits similar emission distribution trends but considerably higher total emissions. For

Materials Research Proceedings 69 (2026) 1018-1023 https://doi.org/10.21741/9781644904251-176

both aircraft, CO_2, H_2O, CO, SO_x, and HC emissions are dominant during the idle phase, mainly due to its long duration, whereas NO_x emissions peak during the climb phase as a result of the combination of intermediate phase duration and higher engine power settings. This comparison highlights that suborbital A-to-A operations, such as those performed by WK2, would have a significantly smaller impact on local air quality than existing large transport aircraft activities, thereby supporting their social and environmental acceptability within civil aviation frameworks. Moreover, total aircraft emissions along the reference trajectory were calculated through the BFFM2 method for the WK2. The trajectory, simulated and validated in the ASTOS environment and complemented by analytically modelled ground phases (taxi, take-off, and landing rolls), is shown in Figure 3 together with emission trends compared with documented FAA estimates [17].





Emissions	Estimated Emissions	Documented (FAA) Emissions
CO_2[t]	21.746	22.962
H_2O [t]	8.477	9.12
NO_x [t]	0.088	0.091
CO [kg]	22.54	12.05
SO_x [kg]	5.47	9.43
HC [kg]	1.95	-

*Fig. 3 - Reference trajectory and total emissions comparison for the WK2 [**17**]*

The discrepancy between the two datasets stems from different mission assumptions: the present work considers idle-to-idle operations, including ground phases, and models variable fuel-flow rates during climb and approach instead of assuming constant power settings. Overall, BFFM2 results demonstrate good consistency. Finally, based on the LTO cycle emission results for both the WK2 and the Dreamlifter aircraft, air quality simulations were performed to assess NO_x dispersion in the Taranto-Grottaglie Spaceport area. The first stage of the analysis involved implementing a simplified analytical model to estimate the average NO_x concentration within the engine plume during the take-off phase. This concentration was calculated using the formulation reported in Eq. (1), derived from the simplified Gaussian plume model, assuming a constant emission mass flow rate Q from a single static source over a 1-minute period representing the take-off duration. The resulting concentrations were time-averaged across the defined spatial grid. The maximum point concentrations for both aircraft occur at the emission source, with corresponding values of 9.9 $\mu g/m^3$ for the WK2 and 153.7 $\mu g/m^3$ for the Dreamlifter. Since the LTO cycle emissions of the Dreamlifter are higher than those of WK2, it is expected and has been confirmed that NO_x concentrations are also higher during the take-off phase. The second stage of the air quality assessment validated the WK2 NO_x estimates from the simplified Gaussian plume model through high-fidelity dispersion simulations using the commercial software LASPORT. Three operational cases were simulated (departure, arrival, and idle) considering a headwind of 3 m/s for both departure and arrival. Near-ground concentrations averaged between 0 and 3 m above ground were computed with a 25 m horizontal resolution and recorded as consecutive 10-minute averages. Figure 4 presents NO_x concentration results for three consecutive 10-minute intervals following take-off. According to the EU Ambient Air Quality Directive 2008/50/EC [23], the annual mean NO_2 concentration must not exceed 40 µg/m³, and the hourly mean must remain below 200 µg/m³. The NO_x concentrations resulting from WK2 operations are well below these regulatory thresholds, further validating the simplified plume model results.

Materials Research Proceedings 69 (2026) 1018-1023 https://doi.org/10.21741/9781644904251-176

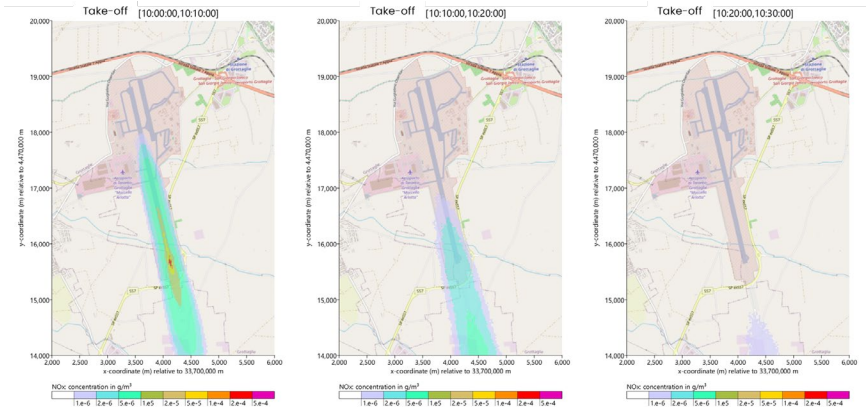


Fig. 4 - LASPORT NO_x concentration results for three consecutive 10-minute intervals following take-off

Conclusions

This work fits within the emerging European context of growing interest in suborbital flight. The study investigated the environmental impact of an A-to-A suborbital mission operating from Taranto-Grottaglie Airport, quantifying chemical emissions of the WK2 carrier enabling SS2's ascent to microgravity and assessing their influence on local air quality at ground level. The air-quality impact was found to be lower than expected, remaining below that of existing operations at the same airport. Consistently with LTO cycle overall emissions comparisons, the maximum NO_x concentration during the WK2 take-off phase is lower than that generated by the Dreamlifter, which performs weekly flights at the reference airport. To validate the concentration results obtained from the simplified Gaussian plume model, a subsequent dispersion analysis of the departure, approach, and idle phases were conducted using the LASPORT tool. The results describe the temporal evolution of NO_x concentrations over 10-minute intervals and constitute an initial step toward broader simulations that account for all airport-related traffic over a representative day at Taranto-Grottaglie Airport. In summary, this integrated workflow translates detailed flight-performance data into quantifiable environmental metrics through a combination of high-fidelity simulation, analytical emissions modelling, and Gaussian dispersion analysis. It provides an adaptable, transparent, and reproducible tool for assessing the atmospheric impact of suborbital carrier operations in mixed-traffic airspace. Beyond its application to the Grottaglie case study and aligned with emerging suborbital regulatory requirements in Italy and Europe, this work delivers a validated methodology for assessing the environmental footprint of reusable launch vehicles in mixed-traffic airspace., bridging the gap between aerospace design and environmental compliance.

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