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Evaluation of environmentally optimal descent and take-off slopes for existing and novel aircraft

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Summary

Descent and takeoff slopes of civil aircraft influence the associated noise and emissions impact around airports. Steep take-off and approach procedures are expected to reduce the noise footprint around airports whereas they could offer local air quality benefits as well. This paper appraises the optimal descent and take-off slopes in terms of noise and emissions for existing civil aircraft, as well as for a future blended wing-body (BWB) concept aircraft. The effect of the interdependencies between noise and emissions is demonstrated, whereas estimated Noise-Power-Distance (NPD) curves for the steep operations are presented. It is shown that a common optimum slope for both environmental concerns is unlikely to occur and that generally, noise benefits come to the expense of increased fuel consumption. However, it is also highlighted that new, more flexible ways of expressing the noise and emissions interdependencies may be required in order to determine optimum slopes more realistically.

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1. Introduction

Forecasts from global air transport stakeholders foresee a significant air traffic grow over the forthcoming years [1, 2]. To compensate for the resulting potential increase of aviation environmental impact [3] ambitious interim-to-long term noise and emissions reduction targets have been set by organisations worldwide like ACARE [4]. Delivering these targets requires not only introducing novel aircraft designs e.g. blended wing-body (BWB) aircraft, and technologies e.g. distributed electric propulsion (DEP), but also contemporary operations, such as steeper approach and take-off procedures that are anticipated as promising ways of exposing less populated areas to aircraft noise [6, 7].

Steep takeoffs at John Wayne airport in California is a representative example of noise abatement take-off procedures. Likewise, Heathrow airport has carried out trials for exploring the effects of a 3.2° slope approach [8], which is slightly steeper than the conventional 3° approach angle; whereas London City airport already includes a glide slope of 5.5° in their 2013 - 2018 noise action plan [9]. However, as discussed in Section 2.1, high glide slopes impose aircraft performance restrictions that limit the types of aircraft that can use airports adopting them.

Normally, mitigation strategies have a simultaneous impact on noise and emissions. Noise impact prediction tools often tend to overlook the interdependencies between the two environmental concerns. It is nowadays acknowledged that accounting for these interdependencies is crucial for effective planning and decision making. Hence, not only does this paper investigate the noise impact of steeper operations, but it also illustrates the concurrent variation of noise and emissions impact with operation angle. It is important to note that the purpose of the presented study is not to exactly predict absolute optimum slope angles values; rather the aim is to provide good estimates of the impact values and capture the associated trends and interdependencies. Another essential output of the study is estimated Noise-Power-Distance (NPD) curves for steeper operations as derived by inputting the estimated noise values into the framework proposed by Synodinos et al. [10]. Included in this paper are representative steep operations NPD curves.

The aircraft models chosen for this study are the Airbus A320-232 and a larger aircraft, the Boeing 777-300. Due to space constraints, this paper only presents two representative cases, i.e. steeper approaches for the A320-232 and steeper takeoffs for the 777-300. Nevertheless the paper additionally presents early estimations for the potential steep approach performance of an hypothetical future BWB aircraft featuring similar mission characteristics as the A320-232.

2. Methodology

Noise calculations are performed using the noise prediction framework for novel aircraft proposed by Synodinos et al. [10]. The framework has already been used to estimate the noise impact of novel DEP [5] and BWB aircraft [10]. In summary, the framework estimates aircraft noise variation arising from operational and/or technological changes with respect to a baseline scenario for which community noise is known. As specified in [10], this is done by first estimating the level change of each aircraft noise source using respective, publicly available noise prediction methods.

The noise prediction methods used in this study are Heidmann's [11] for the fan, Lighthill's acoustic analogy [12] for the jet, and Fink's for the airframe noise [13]. Other methods (e.g. newer) could have been used instead. The baseline scenarios are the default approach and takeoff fight profiles for the A320-232 and the 777-300 respectively. Noise data for the default profiles are publicly available (e.g. in the ANP database [14]). Lastly, the operational and/or technological changes are the trajectory variations along with the associated thrust and high-lift device settings variations that are required for fulfilling the various operations, as specified later in this Section.

2.1. Steep approach

Assessing the steeper approach noise impact is not straightforward. Although at first sight it may seem that doubling the descent angle and thus the distance between aircraft path and receiver can lead to a SPL reduction of almost 6 dB, steep approaches are likely to be accompanied by noise at source increases due to several intermingling factors: Firstly, fulfilling the steep approach requires additional drag (or more generally, altered aircraft lift-to-drag ratio L/D) [6, 7]. For instance, flight-tests in [6] reveal that steep descent of a Boeing 737-800 requires increased flap deflection angles, whereas flyability tests for various aircraft in [7] show that steep approach is associated with deployed landing gears that provide additional drag. To prevent aircraft stalls, the additional drag must be compensated by additional thrust, i.e. increased engine power, which results in increased engine noise. Secondly, increasing flap deflection angle raises airframe noise. Moreover, to fullfil steep approaches, some aircraft may need to be equipped with special devices, such as microdrag generators that increase drag, clam shells that enable the aircraft to descend at a faster rate and ventral airbrakes that serve at maintaining the appropriate approach speed [15, 16]. Due to their high-lift nature these special devices are likely to raise airframe noise. To complicate the situation even further, Mollwitz et al. [7] suggest that steep approach decreased airspeed is controlled by spoilers, at least for some flap deflection angles. So, airframe noise benefits from decreasing airspeed could be outweighed by the noise of spoilers.

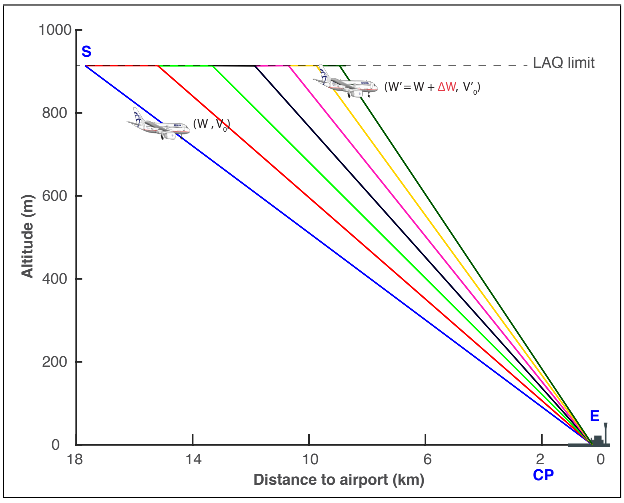

Figure 1. Vertical approach profiles at different slopes for the A320-232. CP is the approach certification point.

Clearly a key point for achieving accurate prediction of the steep approach noise impact is to reliably estimate the associated noise change at source, i.e. the acoustic power change, ΔW. Indeed, this is performed through the framework by Synodinos et al. [10].

The approach angle range examined is from 3° to 6°. This derived based on flyability tests in [6, 7]; further steep approaches concerns like the provision for pilots' training were ignored. Figure 1 portrays the various steep profiles for the A320-232, as obtained through the SAE-AIR 1845 [17] aircraft performance procedure using publicly available data (from e.g. [14], manufacturers websites, etc.) and assuming continuous descent approaches (CDA), as well as a fixed descent rate to satisfy safety and passenger comfort demands. For comparisons to be objective, all approaches are evaluated from a common start point S to the airport (point E). However, the horizontal cruise phase is only significant when assessing emissions.

Table I summarises the configurations, airspeed and thrust variation necessary to fulfil CDA descents at several steep slopes with the test A320-232. The notation 'FULL+' represents hypothetical flap settings for the A320-232 associated with descent slopes higher than 5°, for which appropriate L/D coefficients are obtained through linear extrapolation on the values for the conventional flap settings found in [14].

2.2. Steep takeoff

The environmental impact of steep takeoff is investigated for the Boeing 777-300. Typically, takeoff operation is split into three segments; the ground roll, the initial climb and the continuing climb. Figure 2 gives a visual representation of the examined takeoff profiles, up to the common mission point, E, as derived from the SAE-AIR 1845 [17] aircraft performance procedure. In-detail description of the SAE-AIR 1845

Table I. Airbus A320-232 configuration for various CDA descent slopes.

Angle (deg)	Gear	Flaps ID	Av. airs. (kt)	Dur. (s)	ΔThr. (kN)
3°	Down	3D	144.89	243.3	0
3.5°	Down	3D	143.37	209.7	0.45
4°	Down	3D	141.84	184.6	0.94
4.5°	Down	FULL	140.31	165.0	1.45
5°	Down	FULL	138.78	149.39	2.01
5.5°	Down	FULL+	137.25	136.61	2.59
6°	Down	FULL+	135.72	125.97	3.20

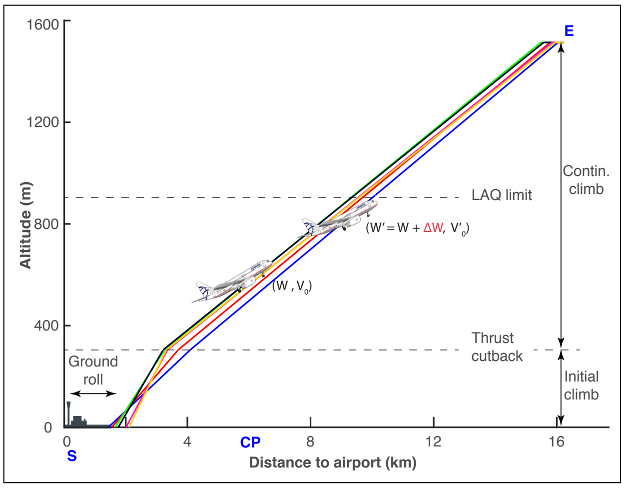

Figure 2. Vertical takeoff profiles at different slopes for the 777-300.

Table II. Takeoff angle and airspeed variation due to different 777-300 configurations at the initial climb segment.

Prof. ID	Flaps ID	ΔThr. (kN)	Airsp. (kt)	Dur. (s)	Angle (deg)
1	L_30_D	-27.40	167.13	47.94	4.24
2	L_25_D	-13.70	178.30	33.83	5.63
3 (def.)	T_20_U	0.00	189.22	21.91	8.21
4	T_15_U	13.70	199.88	18.61	9.16
5	T_05_U	27.40	210.29	16.21	10.00
6	T_00_U	41.10	220.44	13.71	11.30

procedure implementation for deriving the flightpaths can be found in [20]. Nevertheless, it is worth mentioning that aircraft configurations and performance parameters for the three takeoff segments (listed in Tables II – IV) are evaluated by starting from the initial climb, which essentially establishes the initial climb speed that in turn determines the ground roll distance. Also, in contrast to the steep approach case, takeoff angle value is not a direct input, but is determined by the combination of thrust and flap setting.

2.3. Noise-emissions interdependencies

To implement the interdependencies plots, noise and emissions changes are normalised to unity. It must

Table III. Variation of ground rolling parameters with takeoff profile.

Profile ID	Roll. dist. (m)	Av. roll. speed (kt)	Roll. dur. (s)
1	2115	83.56	49.20
2	2247	89.15	48.99
3 (default)	2375	94.61	48.80
4	2500	99.94	48.62
5	2802	105.14	51.80
6	2922	110.22	51.53

Table IV. 777-300 configurations and flight details for each steep takeoff profile at the continuing climb segment.

Prof. ID	Flaps ID	ΔThr. (kN)	Av. airsp. (kt)	Dur. (s)	Angle (deg)
1	ZERO	3.48	187.85	62.60	5.78
2	ZERO	1.72	196.23	60.61	5.72
3 (def.)	ZERO	0.00	204.41	58.84	5.65
4	ZERO	-1.68	212.41	57.26	5.59
5	ZERO	-3.32	220.21	55.83	5.53
6	ZERO	-4.92	227.83	54.56	5.47

be noted that normalisation to unity may not be the optimum way of comparing the effects of noise and emissions. Other existing metrics (e.g. related to cost or annoyance) and/or new ones may express trade-off effects more realistically. Also, it must be considered that the environmental impact of mitigation strategies is to some extent airport-specific; for instance, their effectiveness depends on factors related to the population around an airport, e. g. the number of residents and the location of residential areas. Hence, weightings expressing the effect of such factors could also facilitate a more objective comparison between the impact of noise and emissions.

2.4. Novel aircraft

As mentioned in Section 1, along with contemporary operations, novel aircraft concepts are indispensable for achieving the aggressive long-term environmental targets for aviation. This paragraph investigates the potential noise benefits of steeper approaches when performed by a hypothetical BWB aircraft that has equivalent thrust requirements as the A320-232 and hence features the A320-232 turbofan engines.

It is assumed that the hypothetical BWB aircraft is configured with projected 4 dB airframe noise reduction technologies [10, 21]. Engine noise reduction due to shielding effects of the airframe is ignored in this paper because these effects are likely to be significant only at takeoff [20]. The effects of shielding are demonstrated in [10]. Airframe noise is also assumed to reduce due to the high-lift capability of the BWB that could not only eliminate conventional high-lift devices that significantly contribute to airframe noise, but also provide the short takeoff and landing (STOL) capabilities, i.e. allow steeper procedures (e.g. about 10° approach angles) at lower airspeed. It is reminded that airframe noise scales with the 5th power of airspeed [13]. For including the slower approach effect, a 10% approach speed reduction is assumed.

3. Results

3.1. Steep approach - Airbus 320-232

3.1.1. Noise assessment

The aircraft (i.e. engine and airframe) acoustic power change (ΔW in Figure 1), due to the steep approach configurations (i.e. changes in thrust, flap settings, airspeed) is estimated with Synodinos's framework [10]. To reduce complexity, landing gears are considered to be deployed at the same horizontal distance from the airport independently of descent angle and thus, their noise impact remains fixed for all profiles. Extraction at different lateral distances would induce a new configuration change between standard and steeper descent and an additional noise level change obtainable through e.g. Fink's method. Also, airframe noise variation due to attitude change is ignored.

The left plot of Figure 3 depicts the noise at source variation with approach angle and the noise benefits from increasing the aircraft-receiver distance. The noise increase at source at slopes steeper than 4° is a result of the increased flap deflection angles at these flight profiles. The right plot of the Figure gives the overall noise impact per approach angle; it shows the maximum instantaneous noise level change, $\Delta L_{A,max}$, and exposure level change, ΔSEL, at the approach certification point (CP). Clearly, the noise impact decreases with slope angle. Yet, a more holistic impact assessment requires to also include the emissions impact of the steeper approaches, as shown next. Integrated plots containing noise and emissions impact for the cases examined are summarised in Section 3.4.

3.1.2. Emissions assessment

The typically used methodology in the UK for assessing civil aircraft emissions is the one recommended by DEFRA [18]. Parameters required are the engine power setting, the time period operating at that setting, as well as the associated fuel flow, engine SFC and the NO_x Emissions Indices (EI). These parameters are publicly available, e.g. in the ICAO databank [19] for the default operating modes, i.e. for the conventional approach/takeoff conditions. Values for unconventional operating modes are obtained through interpolation as described in [20]. Table V lists the resulting NO_x EIs corresponding to the thrust settings used in the steeper CDA approach profiles in Table I.

Figure 4 depicts the fuel consumption and emissions impact of various steep approach profiles for the A320-232. While fuel consumption increases with approach angle, descent at 5° seems to optimise NO_x emission.

Table V. Estimated NO_x EIs per descent angle, for the A320-232 engine.

App. angle	3°	3.5°	4°	4.5°	5°	5.5°	6°
EI_{NOx} (g/kg)	5.9	6.0	6.2	6.4	6.6	6.8	7.0

The dashed red line represents the NO_x estimations if the ICAO NO_x EI is used for all approach angles, revealing the importance of accounting for the variation of EI with engine power. The impact in terms of both noise and emissions is shown in Section 3.4.

3.2. Steep takeoff - Boeing 777-300

3.2.1. Noise assessment

The noise impact is extracted by examining the takeoff operation from the start of the ground roll (i.e. the brake release point) until climbing to an altitude where the SPL becomes lower than 20 dB from the maximum experienced SPL. The maximum noise level experienced is the maximum among all segments, whereas SEL derives through logarithmic addition of the segments' noise exposure levels. Figure 5 depicts the noise at source variation with takeoff angle and the noise influence from varying the aircraft - CP distance, for the two climb segments. Noise at source varies in accordance with the flap settings and thrust requirements listed in Tables II, IV.

Also, it is interesting to notice that the aircraft - CP distance is smaller in the 12° takeoff trajectory than in the default one. This is a result of both the additional ground roll distance and the milder continuous climb angle associated with the 12° profile (it must be underlined that this is true for the specific profiles used in this study. Other circumstances could have been assumed and used in the SAE-AIR 1845 calculations, e.g. a variable thrust cutback height or other flap/thrust settings, that would have led to different profiles and hence to different noise at CP. Nevertheless, profile optimisation is out of the scope of this study). Figure 6 illustrates the corresponding noise plot implying that steeper takeoff slopes (at around 9° – 10°) than the default offer small noise benefits.

3.2.2. Emissions assessment

Emissions impact assessment requires including different takeoff segments and sub-segments. Fuel consumption requires not only including the ground-roll, which differs among takeoff profiles, but also setting fixed start and end mission points for all profiles, to ensure objective comparison. Hence, the accounted takeoff period starts from the start of roll and ends at a common point, E, of 2. Likewise, NO_x emissions estimation starts from the brake release point, but ends at the LAQ emissions altitude limit, i.e. 3000 ft.

Table VI outlines the NO_x EIs corresponding to the thrust settings of the climb segments of the steeper takeoff profiles. Figure 7 shows the fuel consumption

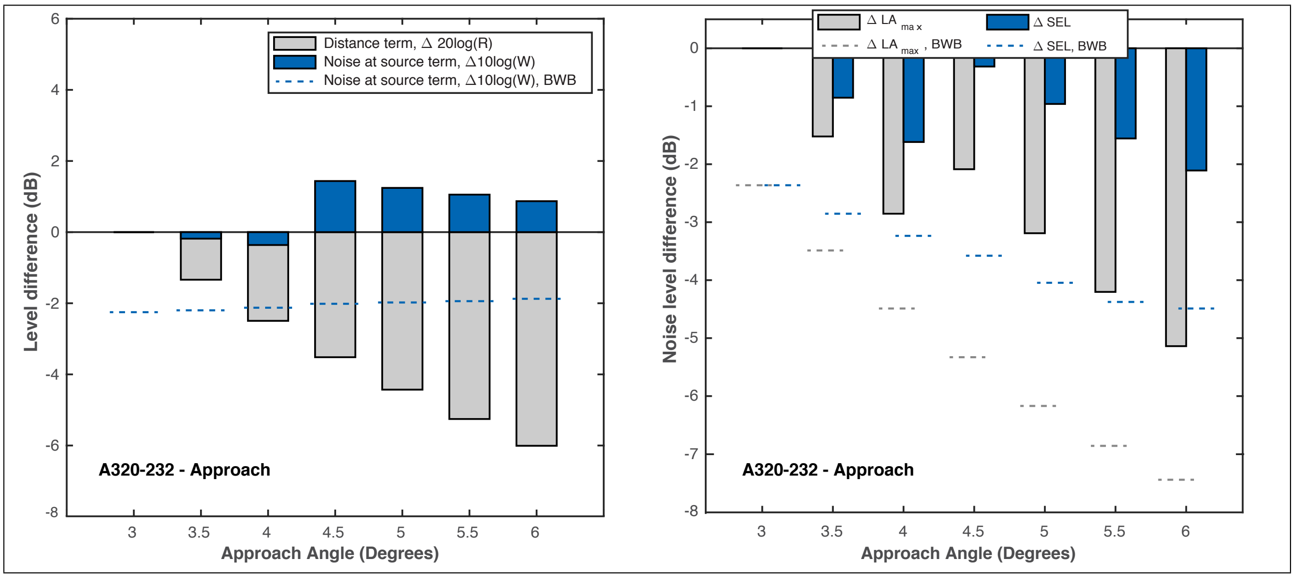

Figure 3. Left: Level difference due to variation of noise at source and of the distance between aircraft and CP with approach angle. Right: Noise level difference at the approach CP between conventional and steeper approach profiles.

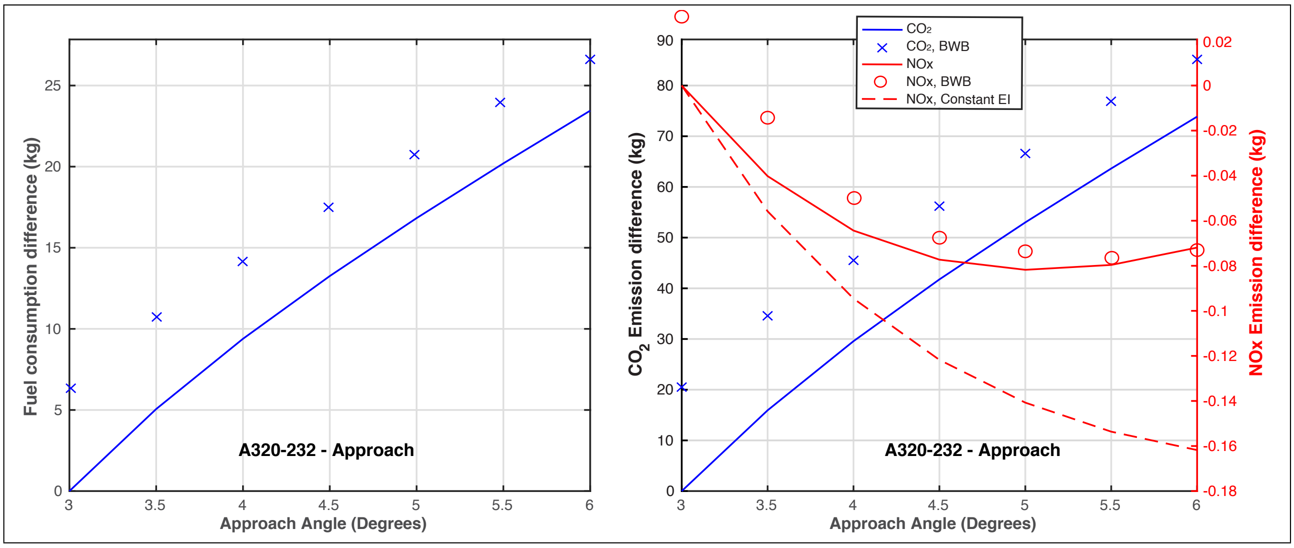

Figure 4. Variation of fuel consumption (left) and emitted amount of CO_2 and NO_x among different steep CDA approach profiles for the A320-232. Crosses and circles represent BWB emission differences from the default A320-232 procedure.

Table VI. Estimated NO_x EIs per takeoff profile for the Boeing 777-300 engine at the takeoff climb segments.

Prof. ID	Seg.	1	2	3	4	5	6
EI$_{NOx}$	**In.**	39.8	41.5	43.3	45.1	46.8	48.6
(g/kg)	**C.**	24.6	24.5	24.3	24.1	23.9	23.8

and emissions impact of various steep approach profiles for the 777-300, implying that the default takeoff profile is optimised in terms of fuel consumption.

3.3. Novel aircraft

The blue horizontal dotted lines in the left plot of Figure 3 show the noise at source level difference between the A320-232 at conventional 3° approach configuration and the hypothetical BWB aircraft at various steeper descent configurations. Since it is assumed that the BWB aircraft has no high-lift devices, the slight noise at source increase with slope angle results solely from increases in thrust requirements.

The grey and blue horizontal dotted lines in the right plot of Figure 3 represent the $\Delta L_{A,max}$ and the ΔSEL between the A320-232 conventional approach case and the BWB steeper approach profiles. Clearly, noise benefits increase with approach angle. Considering that BWB aircraft types could reach approach angles of around 10° this could lead to SEL reductions of at least 5 dB at the takeoff CP. Besides, the small $L_{A,max}$ noise benefits due to reducing the approach speed were found meaningless in terms of SEL due to the resulting elongation of the approach duration.

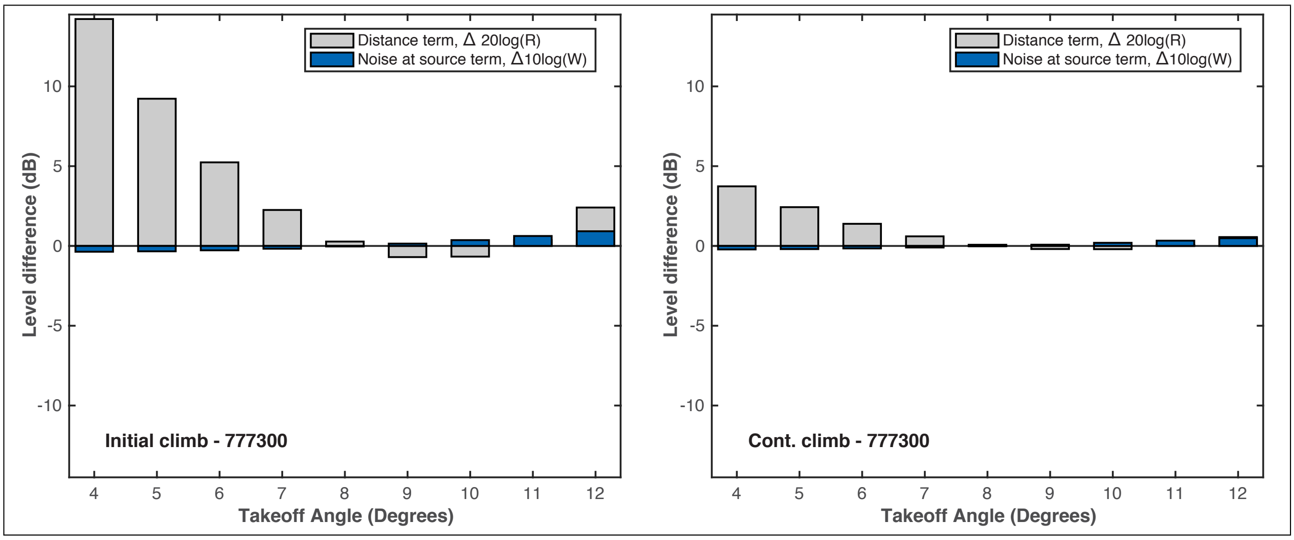

Figure 5. Level difference due to variation of noise at source and of aircraft to CP distance for the 777-300 at takeoff.

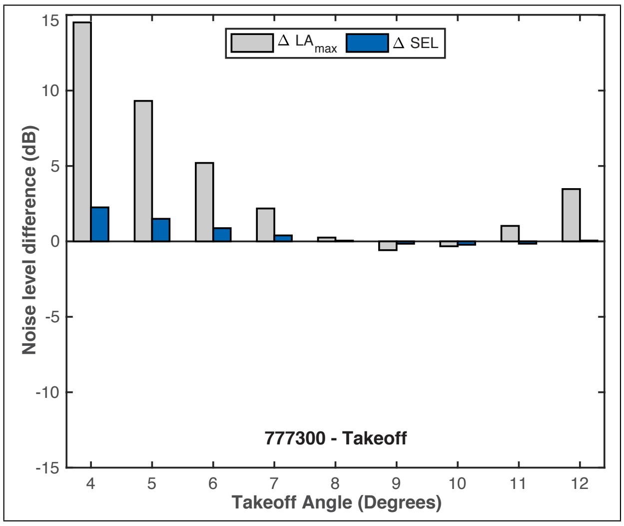

Figure 6. Variation of noise level at the takeoff CP for different steep takeoff profiles for the Boeing 777-300.

Figure 4 shows fuel consumption and emissions differences between the default A320-232 approach case and the BWB profiles. The fuel consumption increase is due to the slower approach and the assumption that the BWB uses conventional engines. Certainly, BWB concepts will be equipped with novel propulsion solutions e.g. DEP [22], which combined with aerodynamic improvements and optimised (steeper than 6°) profiles are likely to notably reduce emissions impact.

3.4. Noise-emissions interdependencies

In Figure 8 the blue and red curves respectively depict the estimated CO_2 and NO_x variation with operation angle, while the green curve represents the noise exposure impact. Generally, it is observed that noise benefits are 'paid' with increased fuel consumption. In the A320-232 approach case, both SEL and NO_x decrease with slope angle but at the expense of increased CO_2 emissions. The abrupt SEL increase occurring at 4.5° results from the high flap settings used at approaches steeper than 4°. Similarly, the 777-300 takeoff SEL impact can be improved by 10% at takeoff angles of around 10°. Although this also results into a 20% NO_x emissions reduction, it comes at the expense of a 20% increase of fuel consumption. Hence, the default takeoff configuration can be roughly characterised as the environmentally-optimum one, since it offers a balanced trade-off between noise and emissions impact. Similar behaviour is observed for the A320-232 takeoff and the 777-300 approach cases (see [20]).

3.5. NPD curves

A critical feature of the noise prediction framework by Synodinos et al. is its capability of computationally estimating NPD curves as analytically described in [10]. In summary, NPD curves provide the relationship between the noise level (in different single event noise metrics) of a given aircraft at a reference flight speed and atmosphere, and the slant distance from the flight path at a number of engine power settings. They are the main input to tools that generate noise exposure contour maps around airports, such as FAA's AEDT [23]. Typically, NPD curves derive through aircraft flyover noise measurements and are therefore available only for existing aircraft and operations. Computationally derived NPD curves allow assessing the potential benefit of unconventional (e.g. steeper) operations and future aircraft concepts (i.e. for scenarios for which empirical data are unavailable) in terms of noise exposure reduction around airports.

Figure 9 shows estimated SEL NPD curves for two representative cases: 5.5° approach for the A320-232, and 11° takeoff for the 777-300. Each curve represents a different engine power setting, F. Dashed lines depict NPD curves for the respective conventional operations. At takeoff, where engine noise dominates,

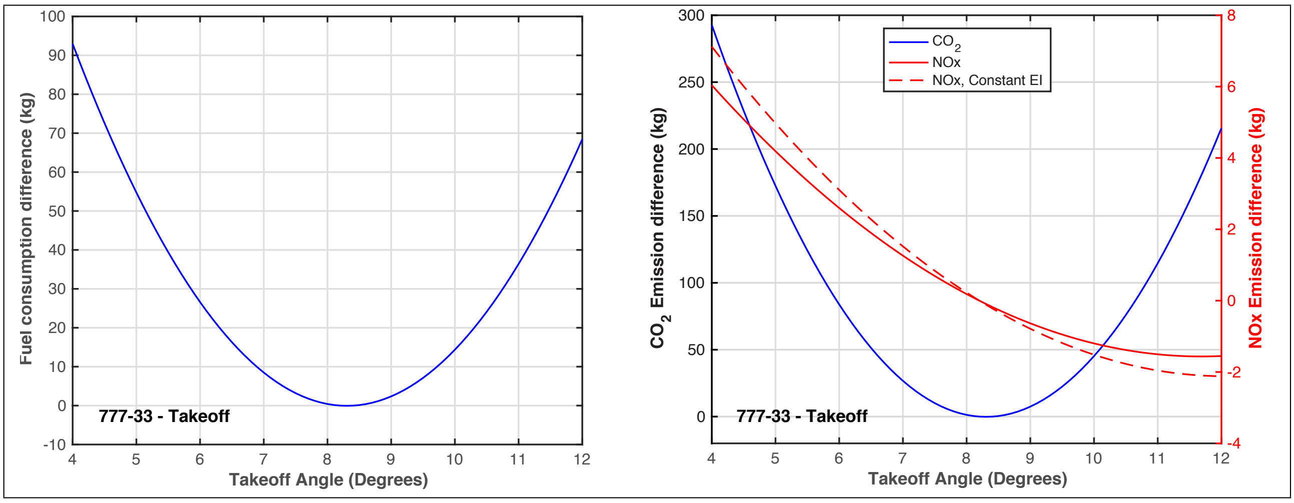

Figure 7. Variation of fuel consumption (left) and CO_2, NO_x emissions among different takeoff profiles for the 777-300.

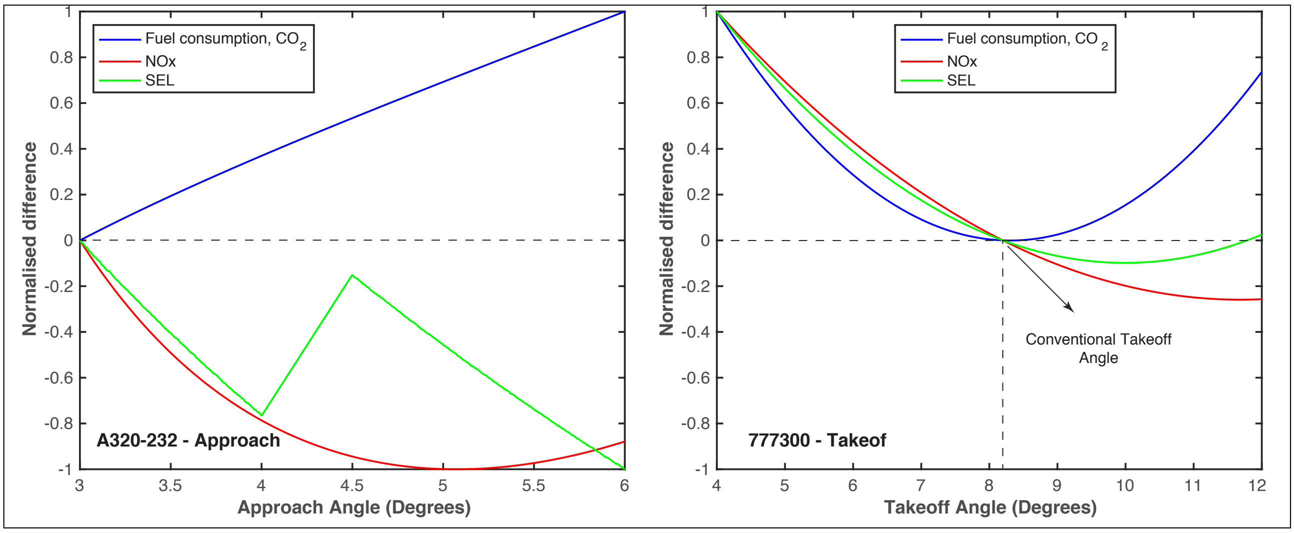

Figure 8. Estimated normalised noise exposure and emissions at different descent angles for the Airbus A320-232.

flap setting changes associated with unconventional configurations generate insignificant noise difference, which practically vanishes at higher engine power settings. In the 5.5° approach configuration, the flap angle is at maximum (see Table I) resulting into a noise rise at source of about 1-2 dB. This is because airframe noise is more important at approach.

4. Conclusions

This paper presented environmental impact estimations for various steeper takeoff and approach profiles for conventional aircraft. Moreover, it was estimated that steep approaches with future BWB aircraft featuring STOL capabilities could lead to dramatic noise exposure reductions. Estimations were performed by feeding publicly available aircraft noise and performance data along with calculated steep profile information into a framework that estimates incremental changes with respect to scenarios where the environmental impact is already known or otherwise obtained. The influence of slope angle on noise and emissions was demonstrated whereas the trade-off between them was depicted by plotting them concurrently in a normalised form. As mentioned in Section 2.3, normalisation may not be the optimum way of expressing these trade-offs, whereas optimum slopes are airport-specific. In this context, it would be interesting to explore new ways of expressing interdependencies between environmental concerns. Possibly, a unit similar in nature to bypass ratio (BPR) could be defined, that could describe the propulsion and/or efficiency effects of new configurations (e.g. lift capability of BWB, etc.) whilst being indicative of their noise characteristics (e.g. BPR has a major effect on propulsive efficiency but is also an indicator of noise).

It is important to note that this study used profiles obtained through the SAE-AIR 1845 procedure under several assumptions (e.g. CDA procedures, fixed

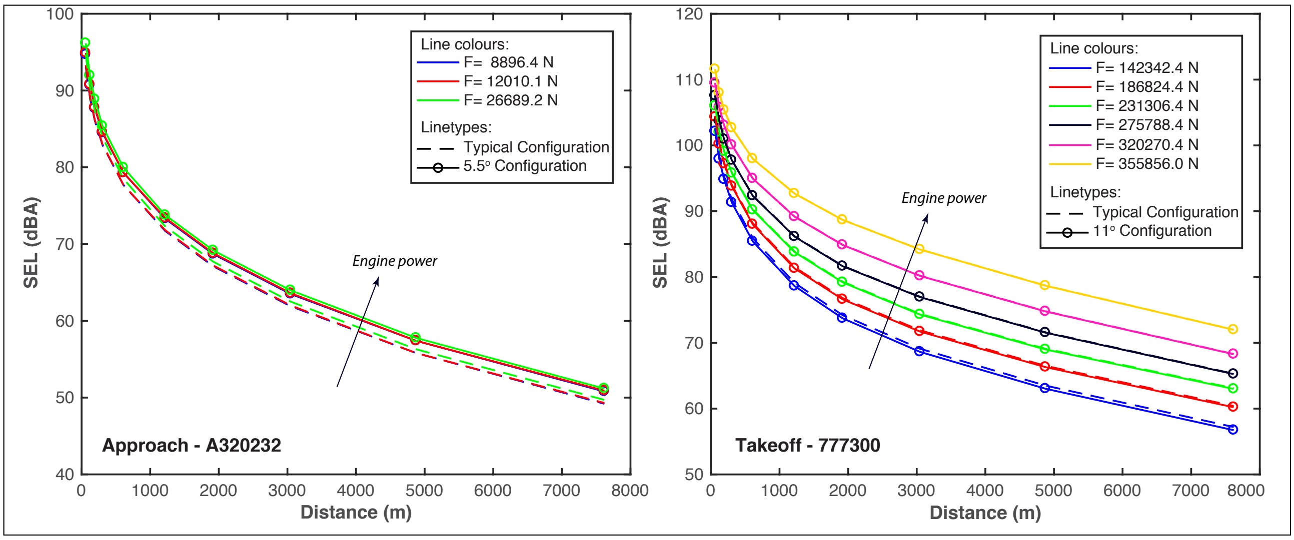

Figure 9. Estimated SEL NPD curves for the A320-232 at steep descent (left) and the 777-300 at steep takeoff configuration. Dashed lines represent published NPDs for the conventional operations. F denotes thrust setting.

thrust cutback height, landing gears deployment at fixed distance from the airport, etc.). Profiles can be optimised for steep operations leading to different results. Finally it is reminded that steep operations combined with technological advances (e.g. new aircraft concepts, propulsive efficiency improvements, quieter engines/airframe, etc.) could lead to further reductions of the civil aviation environmental impact.

Dedication

This paper is dedicated to my wonderful mother, Sophia Synodinou, and my beloved father Panagiotis Synodinos, who passed away on 22 February 2018.

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